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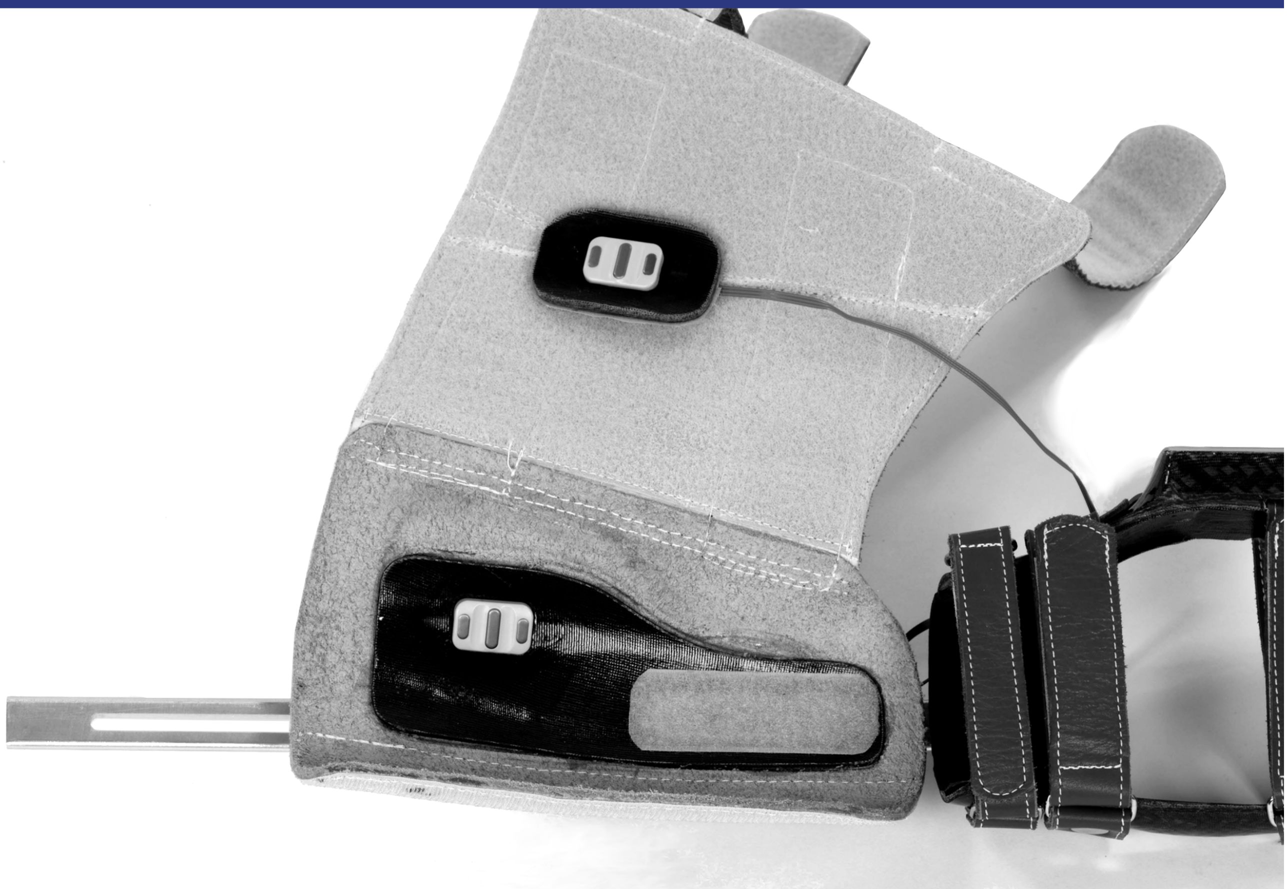

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Hanneke Bouwsema

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Contents

1

Introduction

Our hands are incredibly wonderful parts of our body and play an essential role in our lives. During the day, a huge range of activities are performed with our hands. Think of grasping, holding, and manipulating objects, but also feeling, touching, and for expression during communication. Unfortunately, some people only have one hand or even no hands, due to amputation of the upper limb or a congenital deficiency. For these people, many of the functions of the upper limb are affected. Upper-limb prostheses are developed to restore at least some of these functions. However, the functional use of the current prostheses differs markedly from the human arm and hand. The human upper limb is very complex with bones, joints, and muscles, together providing many degrees of freedom of the moving body parts,[1,2] whereas current commercial available prostheses have only one or at maximum a few degrees of freedom that can be controlled.[3] On top of that, the human hand has a very complex sensory system with proprioception and tactile sense, while the feedback from the current commercial available prosthetic hands is very limited. Moreover, controlling a prosthesis is substantially different from controlling a natural limb, and needs sufficient training.[4] With regard to all these aspects, the main challenge for a prosthesis user is to learn to handle their prosthesis in a dexterous way. Studies on prosthesis use reveal that a high percentage (20% to 40%) of prosthesis users does not use their prosthesis in daily life, which is a clear indication that this is quite difficult.[5-8]

Prosthetic options

At the start of the rehabilitation, novice prosthesis users can choose several prosthetic options. The three main options are cosmetic prostheses, body-powered prostheses, and myoelectric prostheses.[9,10] Cosmetic prostheses do not have active grasping possibilities and mainly serve a cosmetic purpose by replacing the missing hand as naturally as possible. A body-powered prosthesis is actively controlled by movements of the body that are captured by a suspension harness and a cable that runs from the harness to the terminal device. By applying tension to the cable, the terminal device will either open (voluntary opening device) or close (voluntary closing device). This thesis will focus on myoelectric prostheses, since myoelectric prostheses have been increasingly used over the last decades, and research focuses mainly on this type of prostheses.[11,12] A myoelectric prosthesis is controlled by muscle activity. The myoelectric signals from the muscles are captured through surface electrodes that are placed in the socket. After amplification and processing, the signals activate an electric motor to operate the terminal device. Hand opening is accomplished by contraction of the extensor muscles, while closing of the hand is achieved by contraction of the flexor muscles. The amplitude of the generated signals is generally proportional to the contraction of the muscles, and so determines the speed or force of the terminal device.

A myoelectric prosthetic simulator

In this thesis, studies are described that are performed both with experienced myoelectric prosthesis users as well as with able-bodied participants using a myoelectric prosthetic simulator (Figure 1.1). Given the very small number of novice prosthesis users, the prosthetic simulator allowed us to study the process of learning to use a prosthetic device in a bigger group of people. The prosthetic simulator was developed to resemble the use and the control of a myoelectric transradial prosthesis as closely as possible. It consists of a conventional myoelectric hand from Otto Bock, attached to an open socket in which the hand is placed. The prosthetic simulator is attached to the arm with a self-adhesive sleeve that folds around the arm, which is connected to an in length-adjustable splint that runs across the forearm. Two electrodes are placed inside the self-adhesive sleeve to pick up the muscle activity. Activity of the wrist extensors results in hand opening, while the hand is closed by activity of the flexors of the wrist. The simulator is not attached to the hand to prohibit facilitating control. It is hardly possible not to move the hand during contractions of the muscles. Therefore, to mimic control with a stump as closely as possible, most of the movements of the hand are prevented by self-adhesive sleeves that run across the open cast.

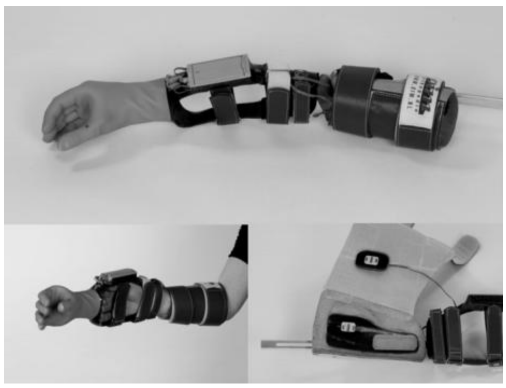

Figure 1.1 *The myoelectric prosthetic simulator. Design and construction: OIM Orthopedie Haren, The Netherlands.*

The rehabilitation process

The ultimate goal of the rehabilitation process is to generalize skills that are learned in the clinic to the everyday situation of the prosthesis user. The rehabilitation process of novice prosthesis users usually consists of a preprosthetic phase, a prosthetic phase, and evaluations. The preprosthetic phase starts, in case of an amputation, immediately after the amputation as soon as the patient is medically stable. It has been shown that it is important to start to train soon after the amputation in order to increase acceptance and use of the prosthesis.[8-9,13-16] During healing of the stump, one can already train in several ways without a prosthesis, such as training of the myoelectric signals. In case of a congenital deficiency, the preprosthetic phase commences when one chooses to wear a prosthesis. The goal of the preprosthetic phase is to prepare the amputee for the use of a functional prosthesis. When the prosthesis is fitted, the prosthetic phase commences. The goal of the prosthetic phase is to bring the prosthesis user to the highest possible level of functional use and acceptance, such that the prosthesis will become an integral part of the patient's life. Training in this phase generally encompasses control training with the prosthesis, goal-directed movement training, and training of activities of daily life. Throughout the rehabilitation, it is important to monitor performance in order to be able to evaluate the learning process over time.[17]

Moving towards evidence-based rehabilitation

It is known that the use and the functionality of a prosthesis increases with training.[18-20] However, to date, it is not known what the most efficient way of training is. Rehabilitation centers often use their own, locally developed training protocols that are mainly based on clinical experience.[5] The demand for a scientifically based training protocol, which is likely to result in the most effective transfer of skills learned in the clinic to the home situation,[21] has lately been increasing.[13,22-32] Such an evidence-based training can be developed once learning processes and movement strategies are well understood. However, literature on how people learn to use a prosthesis is sparse. The majority of the studies on upper-limb prostheses use clinical tests or questionnaires to describe prosthetic function.[17] Generally, these assessments do not provide insight in the quality of the movements performed with the prosthesis, which is required for contributions to improving prosthetic design and enhancing the process of learning to use a prosthesis in a dexterous manner.

Movement patterns with prostheses and deviations from able-bodied movements have been described in several studies, using end-point kinematics or joint angles to examine goal-directed reaching and grasping tasks, or tasks of everyday life. Popat et al.,[33] Carey et al.,[34,35] Highsmith et al.,[36] Bertels et al.,[37] and Metzger and colleagues,[38] focused on body movements in common tasks and movement patterns of daily life. They reported limitations in joint motions due to the prosthesis, which were compensated by movements in the trunk and the proximal upper-limb. Pointing and tracking tasks were studied by Doeringer and Hogan[39], who showed that more movements with the prostheses were necessary to meet an end-point accuracy that was comparable to natural arms. Schabowsky et al.[23] and Metzger et al.[24] showed that prosthesis users were capable of learning new motor skills despite limited feedback provided by the prostheses. Dromerick and colleagues[22] reported improved functionality after training an experienced prosthesis user with a new prosthesis. Prehension was studied by Wallace et al.[40] and Fraser and Wing.[41,42] They described the prehensile patterns of a body-powered prosthesis user and compared these patterns to the unaffected hand. Important characteristics in prosthesis prehension were identified, although the generalization was limited because of only one body-powered prosthesis user was examined in these case-studies.

The use of kinematic analyses in the above-mentioned studies helped to obtain objective information to understand movements performed by prosthesis users. None of the studies, however, provide insight in the learning processes. Motor learning studies can provide a theoretical framework that guides the interpretation of the processes underlying skill acquisition with an upper-limb prosthesis. Numerous theories of motor control have been developed to describe and explain how learning of movements occurs. Generally, motor learning is seen as the process that leads to permanent changes in performance as a result of practice,[21] and the learning process is often described by improvements in the quickness, accuracy, and efficiency of a movement.[1] Many key concepts of motor learning theories are being used in the development of therapies for the rehabilitation setting, such as the structure of presentation of tasks or the provision of feedback.[43] Although the use of concepts of motor learning is not yet common in the clinical practice of upper-limb prosthetics, the application of such strategies can help to facilitate skill learning and enhance the transfer of the learned skills to optimize the performance of prosthesis users in their everyday situation. Moreover, a theoretical framework can provide a foundation for the development of scientifically based training programs, which could make a significant contribution to the rehabilitation of prosthesis users.[13,26-32]

Aim of the thesis

The main aim of this thesis is to increase our understanding of the learning processes during skill acquisition with a myoelectric prosthesis, allowing evidence-based components of training to be developed which may subsequently be used to guide the rehabilitation of novice prosthesis users.

Outline of the thesis

Chapter 2 describes characteristics of the movements executed by experienced myoelectric prosthesis users, which forms the basis for the remaining studies. It provides a kinematic description of performance in prehension and pointing tasks, gaining insight in the way people use their prosthesis during goal-directed movements. Comparison of the characteristic prosthetic movements to able-bodied performance leads to the identification of areas that need attention during training. Before evidence-based components of a training program can be developed however, one first needs to know how people learn to use a prosthesis and what actually determines skills in prosthesis use. Therefore, *Chapter 3* focuses on learning in the preprosthetic phase. Three different types of training are examined. In addition, differences in learning ability are described. In *Chapter 4,* the learning process in the prosthetic phase of rehabilitation is explored. Mimicking the rehabilitation setting, participants practiced with a prosthetic simulator in five sessions spread out over two weeks. The description of the changes in performance contributes to the understanding of motor control processes that underlie movements made with prostheses. *Chapter 5* continues with an examination of the most difficult aspect of learning, the control of grip force with a prosthesis. Virtual grip force training is assessed, and in addition the contribution of augmented feedback is examined. After discussing the learning processes underlying skill acquisition, *Chapter 6* identifies the parameters that define the skill level of prosthesis users. These parameters can be used during the rehabilitation to provide direction to the learning processes. *Chapter 7* moves on to describe how training should be arranged. The concept of contextual interference is applied to examine the structure of the training. In *Chapter 8* the outcomes of the research presented in this thesis are discussed. The combined outcomes resulted in an evidence-based guideline to be used in rehabilitation practice. See the Appendix for further details regarding the guideline.

2

Movement characteristics of upper extremity prostheses during basic goal-directed tasks

Hanneke Bouwsema, Corry K. van der Sluis & Raoul M. Bongers

Clinical Biomechanics 2010, 25, 523-529

Abstract

After an upper limb amputation a prosthesis is often used to restore the functionality. However, the frequency of prostheses use is generally low. Movement kinematics of prostheses use might suggest origins of this low use. The aim of this study was to reveal movement patterns of prostheses during basic goal-directed actions in upper limb prosthetic users and to compare this with existing knowledge of able-bodied performance during these actions. Movements from six users of upper extremity prostheses were analyzed, three participants with a hybrid upper arm prosthesis, and three participants with a myoelectric forearm prosthesis. Two grasping tasks and a reciprocal pointing task were investigated during a single lab session. Analyses were carried out on the kinematics of the tasks. When grasping, movements with both prostheses showed asymmetric velocity profiles of the reach and had a plateau in the aperture profiles. Reach and grasp were decoupled. Kinematics with the prostheses differed in that the use of upper arm prostheses required more time to execute the movements, while the movements were less smooth, more asymmetric, and showed more decoupling between reach and grasp. The pointing task showed for both prostheses less harmonic movements with higher task difficulty. Characterizing prosthetic movement patterns revealed specific features of prosthetic performance. Developments in technology and rehabilitation should focus on these issues to improve prosthetic use, in particular on improving motor characteristics and the control of the elbow, and learning to coordinate the reach and the grasp component in prehension.

Introduction

When one loses part(s) of an upper extremity, a lot of functions of the arm, such as reaching out and manipulating objects, are lost. To restore these functionalities, an upper extremity prosthesis is often used to replace the arm. Although a prosthesis replaces most basic activities of the missing arm it obviously differs from the sound arm and hand. For instance, the human hand has many degrees of freedom of movement and a very complex sensory system, whereas the prosthetic hand is constrained to only one or a few degrees of freedom of movements and it provides very limited sensory feedback. The challenge for the prosthetic user is to perform actions given these limitations in a dexterous way.

The use of a prosthesis is often studied by means of questionnaires.[15,44-46] However, the way amputees actually handle their prosthesis in basic activities of the upper limb, such as pointing to a target or grasping an object, has received only very little attention. This lack of studies concerning prosthetic movements stands in sharp contrast to the numerous studies into pointing and prehension of sound arms and hands.[47-51] Describing the differences between movements made with prosthetic devices and sound hands might contribute to our comprehension of motor control processes underlying movements with prostheses. These insights could advance the design of upper extremity prostheses and training programs to use these devices. Our aim therefore is to characterize movement patterns of the prosthetic arm and hand during pointing and grasping and to compare these patterns with existing knowledge of able-bodied movement patterns.

Both pointing and grasping in able-bodied participants are well-studied tasks.[47-52] Sound prehension is characterized by a bell-shaped velocity profile of the reach. During the reach, the hand gradually opens until a maximum aperture is reached at approximately two third of the reach, after which the hand closes around the object. The start of the reach and the grasp and their endpoint are tightly coupled.[47,48] Pointing movements are also characterized by a bell-shaped velocity profile. The performance of these movements is often described with the use of Fitt's law[52], which describes how movement speed is related to accuracy requirements. Movements with a higher index of difficulty (ID, i.e., smaller targets further away) have longer movement times. The velocity profile changes over task difficulty where a higher ID gives rise to a longer deceleration phase.

Studies concerning movements with prostheses mostly focused on body movements in tasks of daily living.[33-36] Although these studies provide insight into the actual use of prostheses they do not address prehensile patterns or end-point accuracy, therefore, performance with prostheses cannot be compared to existing knowledge of able-bodied performance in reaching and grasping.

Doeringer and Hogan[39] compared performance of both arms of unilateral above elbow amputees using a body-powered prosthesis in a regular pointing, a blind pointing and a tracking task, in which the elbow angle was connected to a target cursor position. They showed that end-point accuracy was comparable between the arms but that more movements with the prosthesis were required to meet the demands of these tasks. Schabowsky et al.[23] compared reaching performance in a novel force-field environment between below elbow amputees using a body-powered prosthesis and able-bodied participants. Early in learning performance was practically similar in both groups while late in learning error was larger in the prosthetic group. Prehension was studied by Fraser and Wing[41,42] and Wallace et al.[40] Only Fraser and Wing reported prehensile patterns and end-point kinematics. They studied one body-powered forearm prosthetic user, and found some distinctive characteristics in the prehensile pattern of the prosthesis. Movement times were longer, hand closure was delayed compared to the sound hand, and the hand showed a plateau in the aperture profile instead of a single peak.

In this study, we characterize movement patterns of prosthetic arms during grasping and pointing movements—using a Fitts' task—and we compare these patterns to known characteristics of sound movements. To reveal the effect of properties of the prosthesis on performance, we evaluate both forearm and upper arm prosthetic users. In prehension, we expect to find a plateau in the hand aperture, as found by Fraser and Wing[41,42], and a decoupling between reach and grasp, especially with the upper arm prostheses due to the mechanical elbow in these prostheses. Positioning and controlling the prosthetic hand while also controlling the prosthetic elbow might be difficult with upper arm prostheses. In the pointing task, we expect that, although Fitts' task has never been used in upper limb prostheses before, Fitts' law should be found in prosthetic pointing movements, since literature has shown that the law applies to many situations[53], including body extensions.[54] Moreover, we used a rhythmic pointing task because it allowed us to characterize the underlying motor control processes.

Methods

Participants

We recruited participants by sending letters to customers of an orthopedic workshop and by placing information on the website of the Dutch national association of amputated persons (the Landelijke Vereniging van Geamputeerden, LVVG). Fifteen people responded. Eight of those were included in the study, all with an acquired amputation, and they satisfied the following criteria: 1) free of neurological or motor problems; 2) normal or corrected to normal sight; 3) daily use of the prostheses, for at least 8 hours a day. Two participants were excluded from further analyses. They could not complete the experiment due to fatigue and technical difficulties. Characteristics of the remaining six participants are presented in Table 2.1. The forearm amputees used myoelectric prostheses; contracting muscles produce myoelectric signals that are picked up at the surface of the skin by sensors built into the socket of the prosthesis to control the motor in the hand. The upper arm amputees used hybrid prostheses, a combination of a myoelectric hand coupled with a mechanical elbow. The elbow functioned by manipulating tension on a cable connected to a harness system fitted around the contralateral shoulder. All participants used Digital Twin® hands (Otto Bock). The study was approved by the Medical Ethics Committee of the University Medical Center Groningen, and the participants gave their informed consent prior to participation.

Table 2.1 Characteristics of the participants

Sex	**Male**	**Male**	**Male**	**Female**	**Female**	**Female**
Age	56	49	41	37	60	30
Level of prosthesis	Upper arm	Upper arm	Upper arm	Fore arm	Fore arm	Fore arm
Type of prosthesis	Hybrid	Hybrid	Hybrid	Myoelectric	Myoelectric	Myoelectric
Years of prosthetic use	20	34	7	1	8	12
Years of usage of present type of prosthesis	4	3	2	1	8	12
Affected side	Right	Right	Right	Right	Left	Left
Hand dominance	Right	Right	Right	Right	Right	Right

Tasks

Three different tasks were examined. In the direct grasping task, participants reached out for and grasped an object positioned on the table in front of them with their prosthetic hand. In the indirect grasping task, participants handed an object over from their sound hand to the prosthetic hand. In the pointing task, participants made horizontal back and forth movements between two vertical bars, with a stylus held in their prosthetic hand.

Apparatus

The positions of both the sound hand and the prosthetic hand were measured using an OPTOTRAK 3020 system (Northern Digital, Waterloo, Canada) recording from above the table. The positions of seven infrared light emitting diodes (LEDs) were sampled with a frequency of 100 Hz. One LED was placed on the ulnar border of the thumb-nail, one along the radial border of the nail of the index finger, and one was placed on the styloid process of the radius of the sound hand. Three LEDs were placed on corresponding positions of the prosthetic hand. The other LED was placed on the object.

For the direct grasping task the initial hand position of the prosthesis was located 15 cm from the edge of the table, in line with the shoulder. The object could be placed at 20, 30, and 40 cm from the initial hand position in line with the shoulder. For the indirect grasping task, the initial positions of the sound and prosthetic hand were 25 cm from the edge of the table, with three distances (20, 30 and 40 cm) between both hands. The object was situated in the sound hand. The midpoint between the two hands was aligned with the body midline. Three wooden cylinders with a height of 10 cm and a diameter of 2, 4, and 6 cm were used in the grasping tasks.

In the pointing task, movements were made with a nonmarking stylus held in the prosthetic hand, on a Wacom Graphics digitizing tablet, connected to a computer running the program OASIS. This provided two-dimensional position coordinates of the pen at a rate of 170 Hz. The targets were printed on laminated A3 sheets, which were attached to the digitizing tablet in landscape orientation.

Experimental design

In a single lab session, the three tasks were presented in separate blocks with the order balanced over participants. For both grasping tasks, the three objects and the three object distances were presented in randomized blocks. The participants had to grasp 45 times in each of the two tasks.

The targets used in the pointing task varied in distance (5, 10, 20, and 30 cm) and index of difficulty (ID) (3, 4, and 5; computed as ID = $\log_2$ (2 * target distance / target size; Fitts[52]). This resulted in 12 conditions, with target sizes varying from 0.31 cm to 7.50 cm in width. These conditions were presented in random order.

Procedure

The participants were seated at a table and commenced with their prosthetic hand closed. For the direct grasping task the participants were instructed to grasp the object with their prosthetic hand and lift it up approximately 5 cm. In the indirect grasping task the participants were instructed to hand over the object from the sound hand to the prosthetic hand, using movement of both hands. No further instructions about the movements of each hand were given.

In the pointing task, the participants performed 40 horizontal back and forth movements with the stylus between two vertical bars printed on a model sheet. Before the start of each movement, the stylus had to be placed on one of the bars. The instruction was to move as rapidly as possible, but keeping errors under 20%. If the participant produced more than two consecutive trials with either zero or too many errors, the participant was told to adjust speed and the trial was rerun. The trial was also rerun if the pen left the tablet. The error rate of 20% was chosen because in the difficult trials, it was hard for the participants to achieve the normally used error rate of 5%[55,56], although a conventional range of IDs was used.

Data analysis

High frequency noise was removed from the position data of the OPTOTRAK LEDs and of the digitizing pen using a second order recursive Butterworth filter with a cut-off frequency of 10 Hz. The position signals were differentiated twice with a 3-point difference algorithm, once to acquire the velocity and again for the acceleration. Trials in which markers were invisible were rejected.

Grasping tasks

The reach was defined as the average of the positions of the LEDs on the index finger and the thumb of the prosthetic hand. For the grasping tasks, the onset and termination of the reach were determined by a 5 cm/s threshold. The time from reach onset until reach termination was the movement reach time; peak velocity was also determined. For both tasks these measures were computed relative to the position of the object—note that the object moved in the indirect grasping task. The grasp was defined by the distance between the LEDs on the thumb and index finger, and maximum hand aperture was determined. The time between grasp onset and grasp termination (determined by a threshold of 2 cm/s) defined movement grasp time. The period from the end of finger opening and the start of finger closure—also determined by a threshold of 2 cm/s—was defined as duration of the plateau phase. We computed onset asynchrony by subtracting the time of grasp onset from the time of reach onset, and termination asynchrony by subtracting the time of grasp termination from the time of reach termination.

Pointing task

The extremes in position defined half cycles. We used half cycles 10 to 35 for analyses. Movement time and peak velocity were averaged over these 25 half cycles. Graphical analyses were done on Hooke portraits (acceleration versus position). In a fully harmonic, rhythmic movement, the Hooke portrait shows a straight line with a negative slope. When the movement is a concatenation of discrete movements—a full stop at the reversal points—the movement of each half cycle ends with a complete deceleration until zero; the Hooke portrait becomes N-shaped. To analyze the harmonic nature of the movements we used a measure of movement harmonicity (H) developed by Guiard[57,58], where H = 1 means a complete harmonic motion, and H = 0 means a pure concatenation of movements.[57-59] A small H indicates that more control is exerted around the targets.

Statistical analysis

Repeated measures ANOVAs were carried out in the grasping tasks with object size (2, 4, and 6 cm), object distance (20, 30, and 40 cm) and task (direct and indirect) as within-subject factors and prosthesis (forearm versus upper arm) as between-subject factor. In the pointing task index of difficulty (3, 4, and 5) and target distance (5, 10, 20, and 30 cm) were used as within-subject factors and prosthesis (forearm versus upper arm) as between-subject factor. When Mauchly's sphericity was violated, the degrees of freedom were adjusted with the Greenhouse-Geisser correction. In all analyses an α of .05 was used, and post hoc tests on main effects used Bonferroni corrections. Generalized eta-squared[60] was used to calculate effect sizes, and interpreted according to Cohen's recommendation[61] of .02 for a small effect, .13 for a medium effect, and .26 for a large effect. Only the effects with an effect size larger than .02 are discussed in the results.

Results

Grasping

In the grasping tasks, 493 trials out of the 540 were analyzed. Figure 2.1 presents typical examples of hand velocity and hand aperture as a function of time and displacement for both types of prostheses in the direct grasping task. The velocity profiles (see Figure 2.1A and 2.1B) were asymmetrical; the acceleration phase was relatively short compared to the deceleration phase. The upper arm prostheses had shorter movement times and trajectories were less smooth than those of the forearm prostheses. All prostheses showed a plateau in the aperture profile (Figure 2.1C and 2.1D). Due to the characteristics of the motor of the hand, velocity of hand opening and hand closing was constant and was almost instantly reached. Overall, hand opening started much later than the reach, and the hand did not close until the end of the reach, that is, when the hand was already around the object (Figure 2.1D).

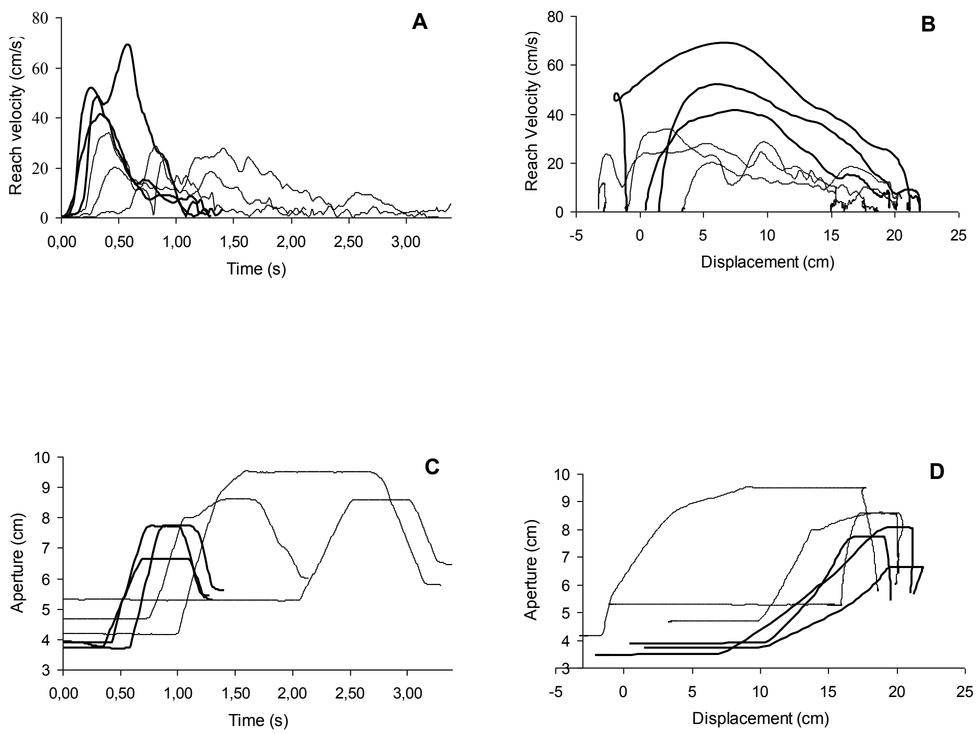

Figure 2.1 *Reach velocity profiles (upper row) and aperture profiles (lower row) of the forearm prostheses (bold lines) and the upper arm prostheses (thin lines) for each participant, plotted for the direct grasping task with an object of 2 cm at a distance of 20 cm. The reach velocity and aperture are plotted against time on the left, and against displacement on the right. Velocity and aperture are aligned.*

The 3D-trajectories of the finger and thumb (Figure 2.2) were smooth trajectories for the forearm prostheses, whereas those trajectories of the upper arm prostheses were interrupted at the moment the elbow was uncoupled in order to direct the hand towards the object.

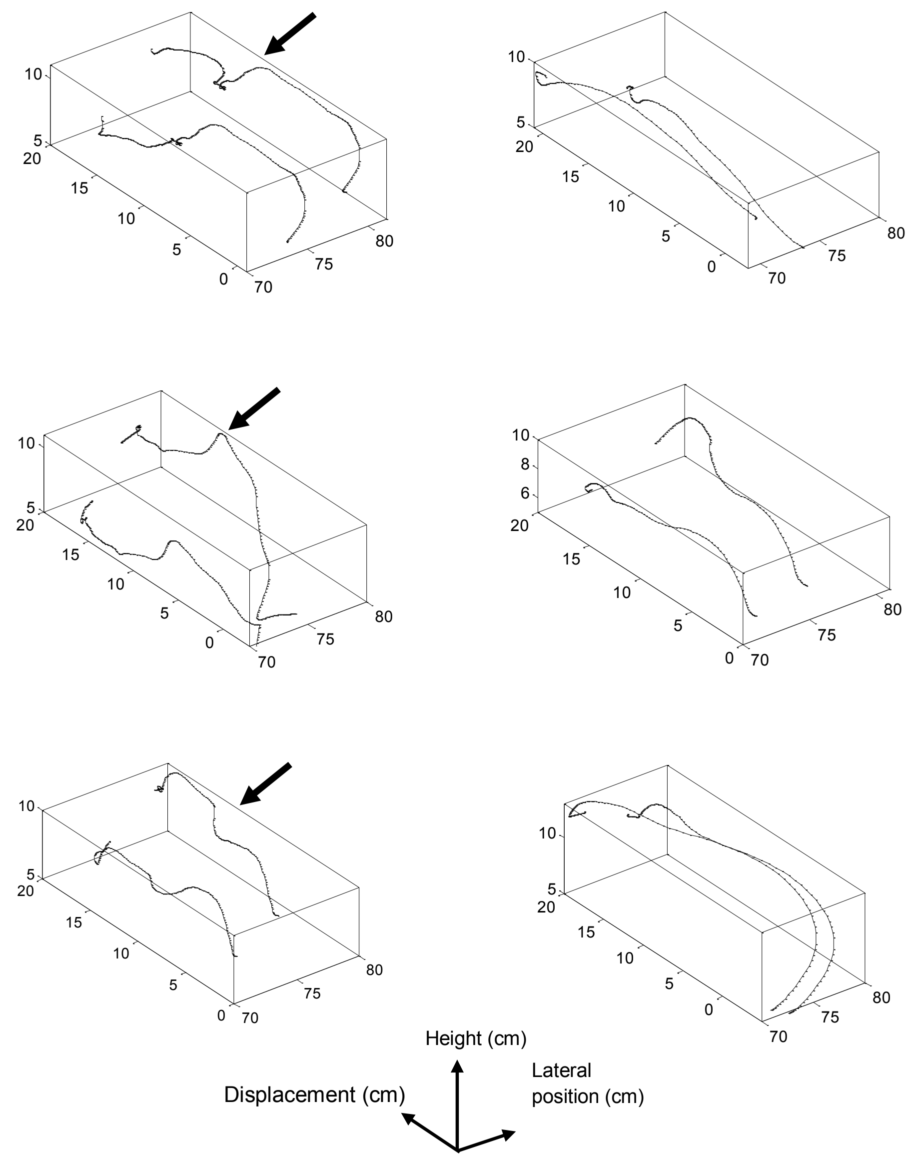

Figure 2.2 *3D plots of the trajectory of the upper arm prostheses (left) and the forearm prostheses (right) for each participant, in the direct grasping task with an object of 2 cm at a distance of 20 cm. The uncoupling of the elbow in the upper arm prostheses is indicated by the arrows.*

Movement reach time

The upper arm prostheses required more time to execute the reach than the forearm prostheses (see Table 2.2). The movement reach time was weakly influenced by object distance. The direct grasping task had significantly longer reach times than the indirect grasping task.

Table 2.2 Statistics for the significant effects

Dependent variable	Within/between subject factor		Mean (SD)	F	*p*	η^2_G
Movement reach time (ms)	Prosthesis	Forearm	1003 (311)	10.16	.03	.47
		Upper arm	1569 (607)			
	Object distance	20	1199 (430)	5.45	.03	.02
		30	1277 (412)			
		40	1358 (418)			
	Task	Direct grasping	1465 (344)	8.91	.04	.23
		Indirect grasping	1086 (508)			
Movement grasp time (ms)	Prosthesis	Forearm	965 (216)	13.67	.02	.58
		Upper arm	1840 (833)			
	Object size	2	1306 (470)	13.87	.00	.02
		4	1338 (424)			
		6	1528 (455)			
Peak velocity (cm/s)	Object distance	20	36.76 (9.9)	93.59	.00	.14
		30	47.39 (10.54)			
		40	54.37 (12.29)			
	Task	Direct grasping	51.72 (67.94)	10.18	.03	.10
		Indirect grasping	39.97 (11.83)			
Maximal hand aperture (cm)	Object size	2	7.71 (1.13)	19.08	.00	.49
		4	8.52 (0.99)			
		6	9.39 (1.06)			
Termination asynchrony (ms)	Prosthesis	Forearm	61 (.13)	9.53	.04	.32
		Upper arm	477 (.62)			

Peak velocity

Peak velocity of the reach was larger for larger object distances. Post hoc analyses showed that all object distances were significantly different (all *p's* $\leq$ .01). Peak velocity was higher in the direct grasping task compared to the indirect grasping task. Although not significant, forearm prostheses had higher peak velocities (59 cm/s, SD 15) than the upper arm prostheses (33 cm/s, SD 11).

Movement grasp time

Grasp time was significantly longer for the upper arm prostheses (Table 2.2). Furthermore, with large objects the movement grasp time was slightly longer than with small objects.

Plateau time

The plateau in the aperture profile had a mean duration of 813 ms (SD 701) for the upper arm prostheses, and 234 ms (SD 183) for the forearm prostheses. However, this difference was not significant, probably due to the large variation in plateau time within the upper arm prostheses.

Maximum hand aperture

Maximal hand aperture was larger for larger objects. Post-hoc pairwise comparisons showed that all the objects differed significantly from each other.

Onset and termination asynchrony

The asynchrony between the start of the hand opening and the start of the reach was on average 351 ms for the upper arm prostheses, and 254 ms for the forearm prostheses, but this difference was not significant. Hand closing ended much faster after the end of the reach for the forearm prostheses than for the upper arm prostheses (Table 2.2).

Pointing

Five of the 72 trials of the pointing task were lost as the cable of the prosthesis of one of the participants broke during the experiment. Figure 2.3 presents the movement trajectories in the pointing task in the form of Hooke portraits (position versus acceleration). For the lowest ID (ID = 3), the almost straight line indicated an almost harmonic movement. With larger IDs the Hooke portrait became N-shaped, indicating that the movement became less harmonic. This was the case for both types of prostheses.

Movement time

The ANOVA showed that a higher ID resulted in longer movement times ($F_{(2,4)}$ = 16.34, p = .01; η^2_G = .46; see Table 2.3 for means and SD). Pairwise comparisons revealed that the ID differed significantly between 4 and 5 (p = .01). MT and ID were linearly related, MT = -.13 + .19 * ID ($F_{(1,64)}$ = 52.41, p = .00; R^2 = .45).

Table 2.3 Mean (SD) for movement time and index of harmonicity (D) for both types of prostheses

		MT		**H**	
TD	**ID**	**Forearm**	**Upper arm**	**Forearm**	**Upper arm**
5	3	422 (.16)	432 (.17)	.38 (.35)	.51 (.31)
	4	546 (.20)	544 (.18)	.35 (.26)	.23 (.18)
	5	801 (.28)	888 (.20)	.03 (.03)	.04 (.05)
10	3	391 (.03)	441 (.09)	.72 (.09)	.62 (.26)
	4	474 (.20)	620 (.13)	.52 (.42)	.21 (.14)
	5	789 (.20)	808 (.15)	.06 (.07)	.08 (.06)
20	3	422 (.02)	472 (.03)	.83 (.07)	.74 (.15)
	4	550 (.13)	643 (.13)	.52 (.27)	.40 (.29)
	5	808 (.23)	878 (.15)	.18 (.14)	.06 (.03)
30	3	397 (.08)	612 (.21)	.90 (.06)	.60 (.37)
	4	806 (.39)	751 (.29)	.48 (.39)	.43 (.50)
	5	670 (.19)	941 (.20)	.48 (.34)	.12 (.10)

TD = target distance (cm); ID = index of difficulty; MT = movement time (ms); H = index of harmonicity

Harmonicity

A higher ID resulted in a lower index of harmonicity ($F_{(2,4)}$ = 22.564, p = .007; η^2_G = .51), as indicated by the N-shaped Hooke portrait with a higher ID. Pairwise comparisons revealed that ID 3 and 5 differed significantly from each other (p = .01).

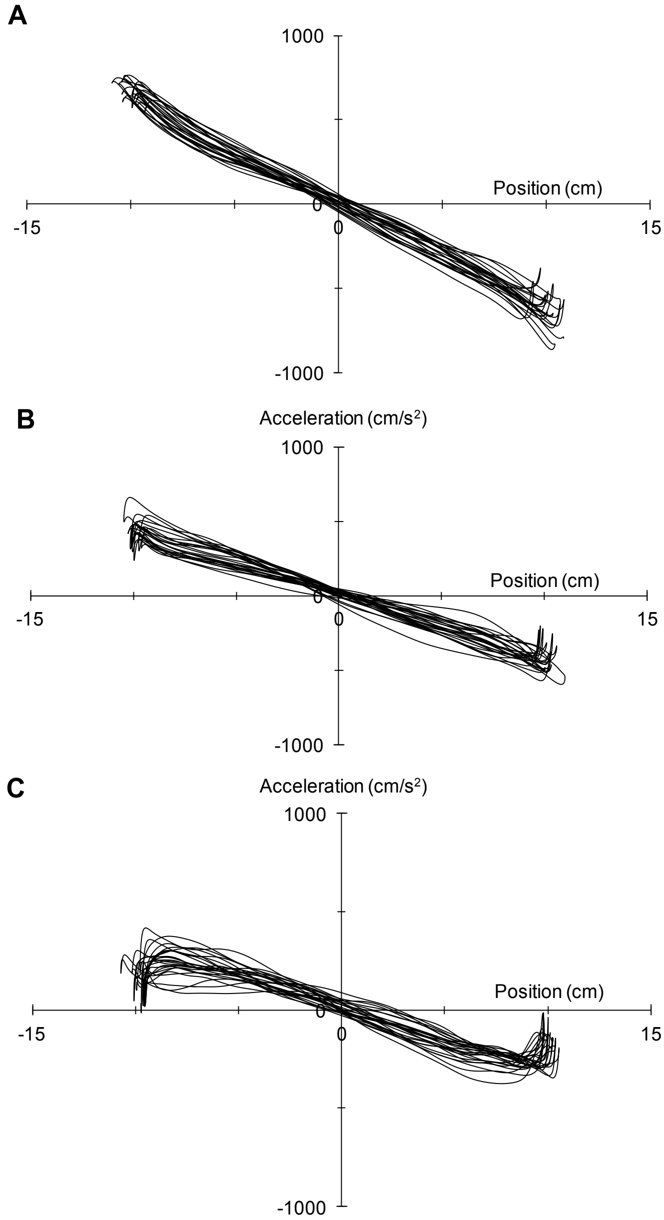

Figure 2.3 *Hooke portraits: acceleration versus position for the three different IDs (ID3 (A), ID4 (B) and ID5 (C)) at a target distance of 20 cm.*

Discussion

Movement patterns with prostheses

In prehension, reach velocity profiles were asymmetric in all prostheses, with a short acceleration phase and a long deceleration phase. As expected, based on the studies of Fraser and Wing[41,42], in prehension the grasp ended later than the reach implicating uncoupling of the reach and the grasp, while the aperture profile showed a plateau. In the pointing task, a higher task difficulty gave rise to longer movement times and a decrease in harmonicity, indicating that Fitts' law applies to prosthetic movements too.

Prosthetic versus able-bodied performance

Prehension with the prostheses was characterized by long movement times, uncoupling of the reach and grasp and, most noticeable, a plateau in the aperture profile. All three characteristics are generally not reported in able-bodied prehension. These differences may originate from several aspects, of which we present two here. First, because of the lack of proprioceptive feedback, prosthetic users must rely primarily on vision.[41,42] Visual feedback is slower than proprioceptive feedback, which results in slower movement speed and, in addition, presumably affects the control of hand closing in particular, resulting in a plateau phase and the uncoupling of reach and grasp. Second, due to mechanical properties of the motor of the prosthetic hand, opening and closing had a constant velocity that was almost instantly reached at the start of hand opening and hand closing. If hand closure were to start immediately after maximum aperture, as in sound grasping, the hand would close too early, before the hand would actually enclose the target. Keeping the hand open at a plateau would prevent this from happening. It would be interesting to study whether the plateau still exists in recent available prosthetic hands with proportional speed control.

The decrease of harmonicity and the longer movement times with higher IDs in the pointing task, are in agreement with what is usually found in able-bodied performance.[56] The shape of the non-harmonic movements of the prostheses in the high ID task indicated that more control is exerted around the targets. Since this is also the case for able-bodied performance, this might suggest that in pointing the prostheses are controlled as a sound hand. However, the movement times of the prostheses were almost twice as long with the same IDs.[54,55] Longer movement times were also found by Baird et al.[54] who studied a Fitts' task in probe usage. Probes, like prostheses, are an extension to the body. However, the movement times in our study were much longer than Baird et al.[54] found. Moreover, in our study, it was not just the increased arm length that influenced performance, since there was no difference in movement time between the two types of prostheses, which differed considerably in length. It seemed that characteristics of the prostheses other than length made the task more difficult to execute, resulting in longer movement times and higher levels of error rate.[55,56]

Differences between the two types of prostheses

The movement trajectories of the upper arm prostheses were less smooth compared to the forearm prostheses, and the movement times were longer in the grasping tasks. As expected, the reach velocity profile was more asymmetric and the reach and the grasp were more decoupled in the upper arm prostheses, probably due to properties of the mechanical elbow. Furthermore, because upper arm muscles tend to co-contract[62], it may be harder to control opening or closing the prosthetic hand correctly, as at the same time the muscles are also needed for the reach action. This suggests that using—and learning to use—an upper arm prosthesis might be more difficult than using a forearm prosthesis.

Future research

The characteristics of prosthetic behavior demonstrated in the present study might guide future research to increase prosthetic use. Prosthetic use needs to be defined in two ways: by the technical possibilities offered by a prosthesis, and by the functionality, the way an amputee handles the prosthesis.[63] Our findings reveal that the function of the prosthetic hand with constant speed, does not resemble natural hand aperture, and, thus, might be disturbing for the user. Prosthetic hands with gradual hand opening might be easier to use because they allow a closer replication of able-bodied grasping. Moreover, it is advised to improve elbow control-systems and to improve myoelectric control schemes of the prosthetic hand so that they are less sensitive for co-contractions, something that now hinders the use of upper arm prostheses. The current results also point to aspects that should be attended to prosthetic training in order to enhance the prosthetics' functionality, such as learning to coordinate the reach and grasp component.

Study limitations

The study had a few limitations. We had only a small group of participants, and therefore, generalizability of our study is low. Another limitation of the study was co-occurrence in our participant group with the hand dominancy and the type of prosthesis used. As Carey et al.[34] stated that previously dominant side does not exert much influence, we do not expect that this influenced our results. An important aspect to note is that we observed the most ideal situation with experienced prosthetic users and a lab setting. We expect that the control of prostheses in daily life is even more difficult because of influences from the environment and the need to perform double tasks.

Conclusions

By characterizing movements with upper extremity prostheses, specific deviations have been pinpointed between two types of prostheses and between prostheses and existing knowledge of able-bodied behavior. Developments in technology and rehabilitation should focus on these issues to increase the use of prostheses, in particular on improving motor characteristics and the control of the elbow, and learning to coordinate the reach and the grasp component in prehension.

Acknowledgements

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3

Learning to control opening and closing a myoelectric hand

Hanneke Bouwsema, Corry K. van der Sluis & Raoul M. Bongers

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Abstract

The objective of this study was to compare 3 different types of myoelectric signal training. 34 Able-bodied right-handed participants were randomly assigned to 1 of 3 groups. The participants trained hand opening and closing on 3 consecutive days. One group trained with a virtual myoelectric hand presented on a computer screen, one group trained with an isolated prosthetic hand, and one group trained with a prosthetic simulator. One half of the participants trained with their dominant side, the other half trained with their non-dominant side. Before and after the training period, a test was administered to determine the improvement in skill. Participants were asked to open and close the hand on 3 different velocities at command. The main outcome measures were peak velocity, mean velocity, and number of peaks in the myoelectric signal of hand opening and closing. No differences were found for the different types of training; all participants learned to control the myoelectric hand. However, differences in learning abilities were revealed. After learning, one part of the participants could produce clearly distinct myoelectric signals, which resulted in the ability to open and close the hand at 3 different speeds, while others could not produce distinct myoelectric signals. To conclude, acquired control of a myoelectric hand is irrespective of the type of training. Prosthetic users may differ in learning capacity, this should be taken into account when choosing the appropriate type of control for each patient.

Introduction

After upper limb amputation myoelectrically controlled prostheses are often provided.[62,64-66] These prosthetic devices are controlled by a myoelectric signal, produced by muscle activity, which controls an electric motor to open and close the prosthetic hand. Producing an appropriate myoelectric signal is imperative to a good control of the prosthetic hand, and is therefore a prerequisite for the functional use of the prosthesis in daily life.[67]

Appropriate myoelectric control is becoming more and more important given the recent technological developments of prosthetic hands, such as proportional control—opening and closing the hand at different speeds—and the control of multiple functions—such as hand opening and wrist rotation—with the myoelectric signal of one muscle site. This means that users have to learn to produce a specific myoelectric signal to control each function of the prosthetic hand.

Importantly, the part of the training focusing on the control of the myoelectric signal has been neglected in the research into prosthetic training.[19,22,23,68,69] Up to now, it has not been examined whether training the control of myoelectric signals after fitting of the prosthesis leads to comparable results as training in the preprosthetic phase—from the amputation until fitting of the prosthesis—with a tabletop prosthetic hand or with a virtual prosthetic hand on a computer screen, the latter becoming more and more available nowadays. Such information is necessary to decide whether novice amputees can start to train myoelectric control early (in the preprosthetic phase) instead of requiring a fitting first.

The aim of our study is to determine which of three training methods currently used in rehabilitation,[9,70] exhibit the strongest learning effect on controlling the myoelectric signal; with a virtual prosthetic hand, a tabletop prosthetic hand—both applicable in the preprosthetic phase—or a fitted prosthesis.

Methods

Participants

Thirty-four able-bodied right-handed participants were studied; 9 men (mean age 21.10 years) and 25 women (mean age 20.04 years). Inclusion criteria were 1) free of any neurological or motor problems; 2) normal or corrected to normal sight; 3) right-handed; 4) no earlier experience with a prosthetic simulator. The study was approved by the local Ethics Committee, and informed consent was given prior to participation. After completion of the experiment, participants received a gift voucher.

Materials

To train myoelectric control with a virtual hand, PAULA® software (Prosthetists' Assistant for Upper Limb Architecture (Otto Bock HealthCare Products GmbH, Vienna, Austria)) was used in conjunction with a 757M11 MyoBoy® with active socket electrodes (13E200 MyoBock Electrodes with a rectified and filtered (2nd order) output, and linear sensitivity controller), connected to a PC. PAULA software can be used to evaluate myoelectric control, by means of feedback presented on the computer screen in the form of electromyographic signals or a virtual prosthetic hand. In this study, the virtual Sensor Hand Speed® was used. The electromyographic signals were registered by a 32-channel PORTI recording system (Twente Medical Systems, Enschede, The Netherlands).

A myoelectric simulator[63] was developed to resemble as closely as possible a myoelectric upper extremity prosthesis for a below-elbow amputation (Figure 3.1). The simulator consisted of the myoelectric hand attached to an open cast to place the hand, and an in length adjustable splint to attach the simulator to the forearm with a self-adhesive (Velcro) sleeve. The myoelectric hand attached was the MyoHand VariPlus Speed® (Otto Bock), with proportional speed control (15-300 mm/s) and proportional grip force control (0-approximately 100 N). This type of hand was also used in the tabletop training condition. For this study the MyoHand VariPlus Speed® of the simulator and the tabletop hand were programmed to act like a Sensor Hand Speed®, thus creating identical features and functions of the hands in all three experimental groups.

Figure 3.1 *The myoelectric simulator.*

To measure the speed and range of opening and closing of the hand an OPTOTRAK 3020 system (Northern Digital, Waterloo, Canada) was used, recording from above the table. Two infrared light emitting diodes (LEDs) were sampled with a frequency of 100 Hz. One LED was placed on the ulnar border of the thumb-nail, and one along the radial border of the nail of the index finger.

Design

Participants were randomly assigned to one of 3 training groups. The first group (V) trained with the virtual hand; the second group trained with a tabletop hand (T); and the third group trained with the simulator (S). Because amputations occur on both sides, one half of the participants trained with their dominant side, while the other half trained with their non-dominant side. The experiment was conducted in 3 days. On the first day, a pretest was conducted after which control of the hand was trained on 3 consecutive days. Group V and T trained hand opening and closing 60 times in each of the sessions; Group S trained a functional task in which an object had to be grasped 30 times—each grasp and release of the object and returning to the start position represented 2 hand openings and closings, equaling the 60 times of the other training groups. After the last training session on the third day, a posttest was administered to determine the level of skill after the training.

Procedure

Fitting of the electrodes

Participants were fitted with the electrodes with help of the PAULA software. The exact positions of the electrodes were determined after palpation of the most prominent contraction of the muscle bellies of the extensors and flexors of the wrist. The sensitivity of the electrodes was adjusted to the upper threshold—a high level of myoelectric signal—for each participant individually. This fitting procedure had to be repeated each day before a training could start to prevent environmental influences, such as perspiration of the skin, influence the myoelectric signals that were picked up by the electrodes. To prevent early learning as much as possible, a maximum of 10 contractions was allowed. The locations of the electrodes were marked, so that the electrodes could be placed at the same position every experimental day. The speed of the hand was set to its maximum.

Pretest and posttest

This study focused only on the myoelectric control of the prosthetic hand. Therefore, we could not use currently available assessments of prosthetic function—like SHAP[71], ACMC[65], or UNB[72]—since all these tests assess the fitted prosthesis in a functional way. Moreover, a lot of these tests are observational or questionnaires. To assess the myoelectric control of the prosthetic hand an objective, dynamic measure of performance was needed. Therefore, we designed a test consisting of 2 parts: 1) provide a maximum myoelectric signal for at least 2 seconds—this was repeated 5 times—and 2) opening and closing the hand to the maximal aperture on 3 different velocities at command. Participants were asked to control hand opening and closing at slowest speed possible, at comfortable speed, and at highest speed possible. All velocities were executed 3 times, in a random order. When the hand was not fully opened or closed, the participants were corrected and instructed again. This test was assessed as pretest and as posttest. The tabletop prosthetic hand was used to register kinematic aspects of the myoelectric control, and to eliminate interference with an attached prosthesis.

Training sessions

During the training sessions, participants were instructed to fully open the hand—an aperture of approximately 10 cm between index finger and thumb—and fully close the hand. Moreover, they were instructed to 'play' with the proportional speed option of the hand. After every 20 times opening and closing the hand, a short break was held to prevent muscle fatigue. The participants that trained with the simulator had to grasp a wooden cylinder (10 cm in height, 6 cm in diameter), placed 30 cm away from the start position of the hand. The start position of the hand was located 15 cm from the edge of the table, in line with the shoulder. The participants were instructed to grasp the cylinder, lift it approximately 5 cm, place it back on the same position, and return to the start position with the index finger and thumb touching each other. They had to perform the movements as rapidly and as accurately as possible. A short break was inserted to prevent muscle fatigue after every 10 grasps.

Data analysis

High frequency noise was removed from the position data of the OPTOTRAK LEDs using a second order recursive Butterworth filter with a cut-off frequency of 15 Hz. The difference between the position of the markers on thumb and index finger of the tabletop hand defined hand opening. Hand opening was differentiated with a 3-point algorithm to acquire opening velocity. Kinematic measures of the opening reflect the control of the prosthetic hand. Peak velocity of the hand opening, peak velocity of the hand closing, and mean velocity over hand opening and hand closing were determined. We rejected trials in which the maximum hand opening was smaller than 95 mm.

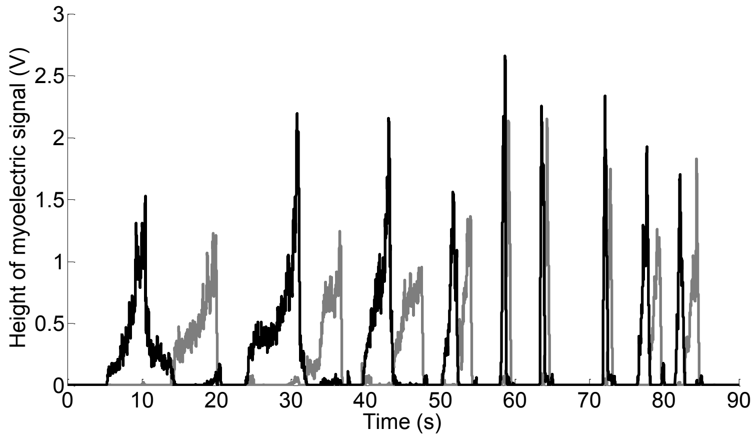
A custom made peak detection program in Matlab determined the local peaks (maxima) in the myoelectric signal. A point was considered a peak if it had a maximum value and was preceded and followed by a value that was more than 7000 μV smaller. The number of peaks was used to measure the smoothness. The amplitude of the myoelectric signal could not be used, since the gain of the electrodes was adjusted to the same level, affecting the maximum myoelectric signal, for each participant every day.

A repeated measure ANOVA was conducted on the peak velocity, the mean velocity, and the number of peaks in the EMG of hand opening and hand closing, with test (pretest and posttest), velocity condition (slow, comfortable, and fast), and direction (opening and closing of the hand) as within-subject factors and training group (V, T, and S) and dominance (dominant side and non-dominant side) as between-subject factors. When sphericity was violated, the degrees of freedom were adjusted with the Greenhouse-Geisser correction. In all analyses a significance criterion of $\alpha \leq .05$ was used, and post hoc tests on main effects used Bonferroni corrections. Generalized eta-squared[60,73] was used to calculate effect sizes, and interpreted according to Cohen's recommendation[61] of .02 for a small effect, .13 for a medium effect and .26 for a large effect. Only the effects with an effect size larger than .02 are presented in the results.

Results

The key question of our study was which of the three training methods had the largest learning effect on myoelectric control. Our results showed that the training groups did not differ in their capacity of myoelectric control (mean peak velocity [95% confidence interval]: V = 450.31 [413.35, 487.26]; T = 468.23 [423.4, 512.98]; S = 418.56 [379.60, 457.51]). Before we present the full analyses demonstrating this, we first show characteristics of the myoelectric signal that led us to include an additional factor in the analyses. The myoelectric signals produced by each of the participants showed many individual differences in the posttest; some participants showed clearly distinct myoelectric signals for the different hand opening and closing velocities, while for other participants the signals were almost equal (see Figure 3.2 for an example).

Because of these apparent differences, we looked further into performance. We calculated the regression lines of the peak velocities in the posttest over the slow, comfortable, and fast velocity conditions for each individual participant. A high slope of the regression line indicates a high relation between the demanded and the performed velocity. Based on the average of the slope of the regression lines (81), we split the participants into 2 different learning categories. Participants with a higher slope were classified as High Capacity Learners (HCL), and participants with a lower slope were classified as Low Capacity Learners (LCL), shown in Figure 3.3. No systematic tendency could be observed in the distribution of type of learning across the training groups ($\chi^2_{(2)}$ = 2.24, p = .33) and across arm dominancy ($\chi^2_{(2)}$ = .79, p = .67). Therefore, statistical differences between groups cannot be attributed to differences in learning capacities of the participants of each group. The type of learning (HCL and LCL) was added to the ANOVAs, presented in the following, as a between-subject factor.



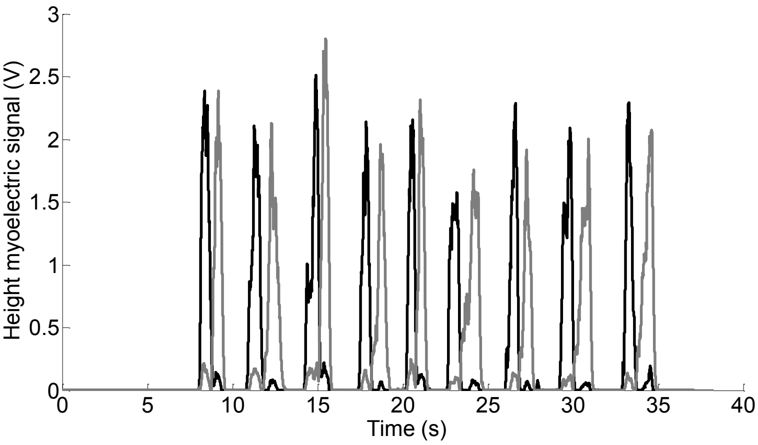


Figure 3.2 *Illustrative examples of myoelectric signals of 2 different participants on the posttest. Top, the 3 different velocity conditions can be clearly seen in the myoelectric signals. The slow conditions are characterized by a wide myoelectric signal, whereas the fast conditions show a very narrow but high myoelectric signal. Bottom, the velocity conditions are difficult to distinguish. Note the different time scales of the 2 figures.*

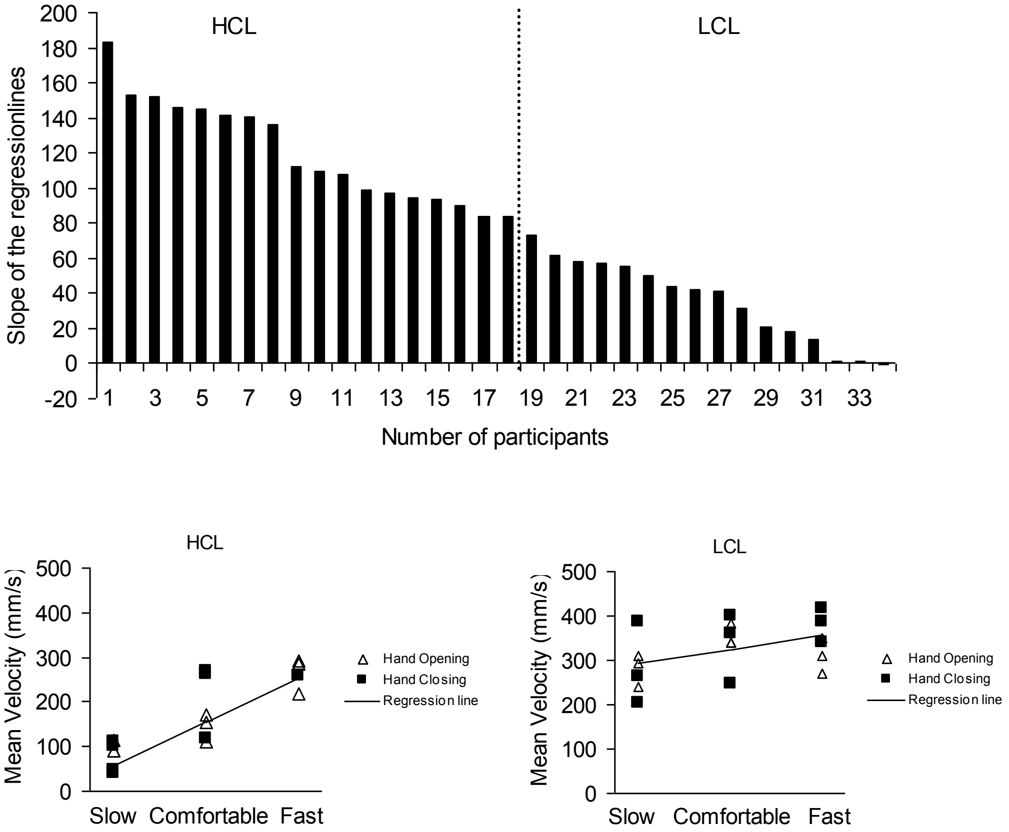


Figure 3.3 *Categorization of participants in High Capacity Learners (HCL) and Low Capacity Learners (LCL), with the division based on the mean slope of the regression lines (81) (A). Figure 3B and 3C show the regression lines of the same HCL participant (3B) and the LCL participant (3C) as demonstrated in Figure 3.2.*

Peak velocity and mean velocity

Both peak velocity and mean velocity showed the same main effects. Importantly, no significant differences were found between the 3 training groups for both dependent variables. A large effect was found for both peak velocity and mean velocity on the 3 velocity conditions (see Table 3.1 for an overview of all significant effects); in the fast condition the participants reached the highest velocities, whereas in the slow condition the velocities were lowest. Moreover, a moderate effect was found on type of learning; HCL reached lower velocities compared to LCL (Figure 3.4). During the posttest, participants reached somewhat higher velocities than in the pretest.

Table 3.1 Significant effects

Dependent variable	Within/between subject factor(s)	F	*p*	η^2_G
Peak velocity (mm/s)	Velocity	82.02	.00	.28
	Learning Type	18.87	.00	.12
	Test	54.54	.00	.08
	Arm	9.77	.00	.06
	Velocity * Learning Type	18.23	.00	.09
	Test * Velocity * Learning Type	7.05	.01	.03
Mean velocity (mm/s)	Velocity	68.88	.00	.28
	Learning Type	9.39	.01	.12
	Test	30.92	.00	.05
	Arm	19.84	.00	.06
	Direction	19.80	.00	.03
	Velocity * Learning Type	7.86	.01	.05
	Test * Velocity	7.37	.01	.03
	Velocity * Direction	11.47	.00	.02
Number of Peaks	Velocity	44.93	.00	.32
	Learning Type	15.32	.00	.09
	Test	36.94	.00	.02
	Group	6.02	.01	.07
	Velocity * Learning Type	10.64	.00	.11

A small to moderate interaction effect of velocity and learning revealed that while both learning types reached almost equal velocities in the fast condition, the HCL could reach much lower velocities in the slow condition compared to the LCL. The effect sizes of the other significant effects in Table 3.1 are rather small and will not be discussed further.

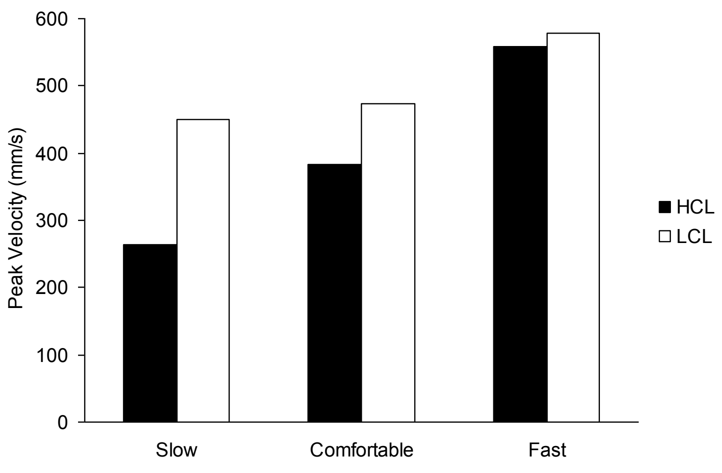


Figure 3.4 *Peak velocity reached in the pretest and the posttest for the High Capacity Learners (HCL) and Low Capacity Learners (LCL), plotted for each of the velocity conditions.*

Amount of peaks

Analysis of the number of peaks in the EMG revealed the same effects as reported on the peak velocity and the mean velocity. A large effect of the velocity conditions showed that in the slow condition the most peaks occurred, while in the fast condition the fewest number of peaks were shown. The number of peaks in the posttest was somewhat less than in the pretest. Learning type showed a small to moderate effect; the HCL showed more peaks in the EMG than the LCL. The moderate interaction between velocity condition and learning type revealed that while the number of peaks was rather equal in the fast condition for both learning types, the HCL showed more peaks in the slow condition compared to the LCL. A small effect of training group was found—which was different from the peak velocity and the mean velocity. This effect was mainly due to 2 participants in the simulator group, who had relative to the other participants much more peaks in the slow condition. Rerunning the ANOVA with exclusion of these 2 participants revealed no effect of training group ($F_{(2,18)} = 1.96$; $p = .17$)), while rerunning the ANOVA 4 times with exclusion of 2 randomly chosen participants showed the significant effect again. This provides evidence that the small effect of training group is only due to the performance of these 2 participants.

Discussion

The purpose of this study was to determine the training method with the highest effect on control of the myoelectric signal. Importantly, no differences were found between the 3 types of training, suggesting that training the myoelectric signal with a virtual or tabletop hand leads to comparable control of the prosthetic hand as functional training with a fitted prosthesis. Training with a virtual or a tabletop prosthesis can be provided in the preprosthetic phase to train independent and correct activation of the stump musculature for basic myoelectric functions[70], while functional training is only possible after fitting of the prosthesis in the prosthetic phase. Our findings validate the use of virtual and tabletop prosthesis training instead of requiring a fitted prosthesis to train control of the myoelectric signal.

Moreover, our findings imply that early in rehabilitation (i.e., in the preprosthetic phase) the level of control of a patient can be determined. Skills learned during preprosthetic training are important for motivation and success with the prosthesis[70]. Given that the most recent prosthetic hands are also available as virtual hands, early start of training might speed up the complete rehabilitation process, including the selection of the most appropriate prosthetic components. This might be beneficial for prosthetists, patients, and insurance companies.

Importantly, at all phases of the experiment, all participants were able to generate a myoelectric signal that opened and closed the prosthetic hand. After training, higher velocities were reached in most conditions, which is probably due to more specific muscular control. This finding is in agreement with the study of Corcos et al.[74], who showed that after training over a single joint—in their study the elbow—the peak velocities increased.

An interesting finding was that although all participants learned to open and close the hand, there were differences in the learning capacities; high capacity learners (HCL) could make a good distinction between the 3 different velocity conditions in the posttest, whereas low capacity learners (LCL) could not make this distinction. It seemed that the LCL had learned how to open and close the hand, but could only contract their muscles in a single way, resulting in an almost invariable hand opening and closing velocity. They were not able to vary the myoelectric signal to fully utilize the available options of the proportional control of the prosthetic hand. Such a difference in learning abilities is also observed in rehabilitation practice. It is generally known that some patients can easily learn to use their prosthesis, while others are less proficient, suggesting that prosthetic users differ in learning capacity. If differences in learning capacity actually exist, it should be taken into account when choosing the appropriate control type for each individual patient. A patient who is skillful in myoelectric control would benefit more from a proportional control type, whereas a patient with less proficient myoelectric control might be better off with an on-off switch control type. This suggests that patients should be fitted with the most appropriate control system, which might increase the chance of acceptance and use of the prosthesis. Moreover, it could be that—at least a part of—the LCL might be able to learn proportional control too, but this might take longer than the 3 days of training used in this study. More research is needed to be able to make a better distinction between different types of learners.

In this study, we used able bodied participants instead of recently amputated patients. With able-bodied participants, we did not have to bother the very small group of patients who had just been amputated and could therefore test more subjects. A recent study of Schabowsky et al.[23], studying motor performance in amputees as well as able-bodied participants, showed that the learning skills of the amputees were similar to the unimpaired participants. Although we expect to find similar results of our study in amputated patients, further research is needed to establish the generalization of our findings to the amputee population. Another limitation of the study is the fact that we divided the participants post hoc into different learning capacities. We did not expect to find differences in learning beforehand, however, this interesting finding was worthwhile mentioning. In future experiments, it is recommended to define possible differences in learning ability in advance.

In conclusion, learned control of a myoelectric hand is irrespective of the type of training—with a virtual hand, an isolated hand, or a prosthetic simulator. Prosthetic users may differ in learning capacity; this should be taken into account when choosing the appropriate type of control for each patient.

Acknowledgements

We would like to thank Anne-Wil Koopman, Sanne Roeles, and Auke Noordam for assisting with the data collection and Johan Horst and Theo Schaaphok (OIM Orthopedie, Haren, The Netherlands) for constructing the simulator.

4

Changes in performance over time while learning to use a myoelectric prosthesis

Hanneke Bouwsema, Corry K. van der Sluis & Raoul M. Bongers

Submitted

Abstract

Training increases the functional use of an upper limb prosthesis, but little is known about how people learn to use their prosthesis. The aim of this study was to describe the changes in performance with an upper limb myoelectric prosthesis during practice. The outcomes of the study could provide information on how the neuromotor system learns to incorporate the characteristics of the prosthetic arm. The results provide a basis to develop an evidence-based training program. Thirty-one able-bodied participants took part in an experiment as well as thirty-one age- and gender-matched controls. Participants in the experimental condition, randomly assigned to one of four groups, practiced with a myoelectric simulator for five sessions in a two-weeks period. Group 1 practiced direct grasping, Group 2 practiced indirect grasping, Group 3 practiced fixating, and Group 4 practiced a combination of all three tasks. The Southampton Hand Assessment Procedure (SHAP) was assessed in a pretest, posttest, and two retention tests. Participants in the control condition performed SHAP two times, two weeks apart with no practice in between. Compressible objects were used in the grasping tasks. Changes in end-point kinematics, joint angles, and grip force control, the latter measured by magnitude of object compression, were examined. The experimental groups improved more on SHAP than the control group. Interestingly, the fixation group improved comparable to the other training groups on the SHAP. Improvement in global position of the prosthesis leveled off after three practice sessions, whereas learning to control grip force required more time. The indirect grasping group had the smallest object compression in the beginning and this did not change over time, whereas the direct grasping and the combination group had a decrease in compression over time. Moreover, the indirect grasping group had the smallest grasping time that did not vary over object rigidity, while for the other two groups the grasping time decreased with an increase in object rigidity. A training program should spend more time on learning fine control aspects of the prosthetic hand during rehabilitation. Moreover, training should start with the indirect grasping task that has the best performance, which is probably due to the higher amount of useful information available from the sound hand.

Introduction

Training programs used nowadays to learn to use an upper limb prosthesis are still clinic specific[5], rather than evidence-based practice.[28,31] Therefore, it is not known whether a certain training protocol is the most efficient training to facilitate acquisition of prosthetic skills.[5] Hence, there is a growing support for the need of an evidence-based training program.[22-25] To be able to develop such an evidence-based training, knowledge is needed about how people learn to use their prosthesis. Although motor control processes underlying prosthesis use have been examined in a couple of studies[19,23,24,34-36,38,39,75], there has been no research to date—to the knowledge of the authors—that studies motor learning processes of goal-directed actions with prostheses over a period of time during multiple practice sessions. This study aims to describe the changes in use of a prosthetic device during practice. The insights of this study can be used to develop an evidence-based training program, and, moreover, might help us understanding underlying motor learning processes.

In general, motor learning is seen as a process that leads to permanent changes in the ability of the learner[76], and is characterized by the changes in performance over time. Although there is no general definition of motor learning, the process is often described by an improvement in the quickness, accuracy, and efficiency of a movement.[77-80] These aspects will therefore form the basis of the outcome measures that will be examined in this study. Next, transfer of performance improvement is investigated in separate testing sessions, as the most important goal of motor learning in rehabilitation is the generalization of the practiced tasks in the clinic to other activities in daily life.

When training an individual, several factors can be addressed to promote the process of motor learning and skill acquisition in general, such as instructions, types of tasks, type of feedback, amount of practice, or the presentation of tasks.[81-83] This study focuses on three aspects that might be important to study when learning to use a prosthesis: 1) practice effects over repetitions of individual movements and sessions, 2) the type of tasks practiced, and 3) practice conditions to study grip force control.

The first aspect, effects of practice, is included in the study to capture learning processes over time during multiple practice sessions. This allows us to examine how people learn to use a prosthesis over time. Learning a new skill takes time[84], and, moreover, distributing practice sessions across days instead of only one day of practice—a single day is often the case in motor control learning studies[84]—results in enhanced performance[85] (see[77,86] for studies in rehabilitation practice). Since this is the first study that examines learning processes of functional, goal-directed tasks executed during multiple practice sessions with a prosthesis, we applied a broad range of outcome measures, including changes in performing functional tasks and changes in movement coordination. For the latter, changes in kinematics of the movement were examined, which is novel. Based on earlier studies the kinematic variables of primary focus will be reaching and grasping time, the plateau phase in the hand aperture that characterizes coordination of hand opening and hand closing in prehension with a prosthesis, fixation time, and joint angles.[75,41,42] Results could reveal in what way motor coordination improves to provide hints as where to focus on during a training program.

Second, it is important to know what types of tasks need to be practiced to optimize learning.[87,88] The tasks included in this study are based on the actions that are performed with a prosthesis during daily life: direct grasping, indirect grasping—handing over an object from the sound hand to the prosthetic hand—and fixating.[89] Each task was studied separately to be able to extract information concerning the learning processes for each task individually in three separate groups. The changes in performance per task can then be studied, which provides information about the best task to facilitate learning, while the combination of tasks in a fourth group resembled rehabilitation and daily life more closely.

The third aspect in this study concerns grip force control of the prosthetic hand. Modulating grasping forces with a prosthetic hand is a skilled dexterous activity that is not easily mastered, and a good level of grip force control is one of the highest goals in rehabilitation.[70] Good grip force control is very difficult for prosthesis users since most of the feedback—including proprioception and tactile sense—lacks in prostheses. Several studies have already shown that prosthesis users are able to improve grip force control despite the lack of feedback.[24,90,91] To examine the grip force control in this study, objects were used that differed in compliance and therefore required different amounts of grip force.

The main goal of the current study is to describe the changes in performance over time that take place while learning to use an upper limb prosthesis. The study was designed to answer the following questions: 1) what are the changes in the movements over time; 2) how do the different types of tasks influence the learning process; and 3) do the participants learn to control grip force, and if so, how does this process develop throughout the learning sessions. For this purpose, able-bodied participants trained tasks with a prosthetic simulator for five sessions over a two week period.

Methods

Participants

An experimental group (15 males and 16 females; mean age (SD) = 20.27 (2.35) years) and an age- and sex-matched control group (15 males, 16 females; mean age (SD) = 21.2 (2.18) years) participated in the study. All participants were able-bodied, had normal or corrected to normal vision, were right-handed, and had no earlier experience with a prosthetic simulator. For the learning sessions, the participants in the experimental group were randomly assigned to one of four learning groups. One group learned direct grasping (DG, N = 8), one group learned indirect grasping (IG, N = 8), one group learned fixating (FIX, N = 7), and one group learned a combination of all three tasks (COM, N = 8). The participants in the control group only performed two tests and did not practice in between. The study was approved by the local ethics committee (METc application NL26993.042.09) and an informed consent was signed before the start of the experiment. The participants received a gift voucher afterwards.

Apparatus

The myoelectric simulator was developed to closely resemble a myoelectric forearm prosthesis (Figure 4.1), consisting of a myoelectric hand (MyoHand VariPlus Speed®, Otto Bock, with hand opening and hand closing speed between15-300 mm/s and grip force control between 0 and 100 N). The height of the myoelectric signals was proportionally related to the hand opening or closing speed of the hand or the grip force, depending on whether the hand closing was resisted. The hand was attached to an open cast in which the hand could be placed and a splint along the forearm. The splint was adjustable in length and was attached to the arm using a self-adhesive (Velcro) sleeve. The hand was controlled by changes in the electric muscle activity, detected by two electrodes that were placed on the forearm. Activation of extensors opened the hand whereas flexors closed the hand. The exact positions of the electrodes were determined after palpation of the most prominent contraction of the muscle bellies of the extensors and flexors. Subsequently, these locations were marked to place the electrodes. To check the correct position of the electrodes, the Prosthetists' Assistant for Upper Limb Architecture (PAULA, Otto Bock®) was used to visualize the myoelectric signals, in conjunction with 757M11 MyoBoy® connected to a PC. In this way the placement of the electrodes could be such that the highest myoelectric signal could be produced. The sensitivity of the electrodes was adjusted to the high level (66) as indicated by the MyoBoy and PAULA.

Figure 4.1 *The myoelectric simulator*

Three Optotrak 3020 systems (Northern Digital, Waterloo, Canada, sampling frequency 80 Hz) were used to record the positions of 30 infrared light emitting diodes (LEDs) attached to the trunk, the prosthetic arm, and the objects. One LED was placed on the ulnar border of the thumbnail, and one along the radial border of the nail of the index finger of the prosthetic hand. Four rigid bodies, triangles of hard PVC with a LED in each corner, were fixed according to Van Andel et al.[92] One rigid body was placed laterally on the prosthetic wrist just proximal to where the radial and ulnar styloid would be, one on the upper arm just below the insertion of the deltoid muscle, one on the flat surface of the acromion, and one on the manubrium of the sternum. Two LEDs were placed on each of the objects used in the tasks.

A Bertec force plate (sized 40 cm x 60 cm, sampling frequency 300 Hz), synchronized with an Optotrak Data Acquisition Unit, was used to measure forces applied to the table surface in the fixation tasks. The force plate was placed on top of the table in front of the participant. The increased height was corrected by a wooden platform of the same height as the force plate, placed underneath the participants' chair.

The Southampton Hand Assessment Procedure (SHAP)[71] was used during pretests, posttests, and retention tests to capture transfer of performance improvement in tasks other than learned. SHAP consists of 26 tasks: 12 abstract object tasks—6 lightweight and 6 heavyweight objects—and 14 activities of daily living (ADL) tasks, and evaluates functionality of the hand. Time scores of each task result in an overall Index of Functionality score (IoF). The IoF is a score of hand function, a sound hand scores normally between 95 and 100; lower scores reflect decreased hand function.[71]

Three deformable objects and one solid object were used (6 cm x 3.5 cm x 9 cm) as objects in the grasping tasks. The deformable objects consisted of 2 plates with a spring between these plates (Figure 4.2). Each deformable object had a spring with a different resistance, requiring a different grip force before the object deformed—low-resistance object (LO; c = .17 N/mm); moderate-resistance object (MO; c = .57 N/mm); and high-resistance object (HO; c = 5.31 N/mm). The deformable objects simulated objects used in daily life, like a carton or a plastic cup. To simulate object manipulation—like opening the carton—a Velcro cover, mounted on top of the four objects, had to be pulled off from front to back of the object.

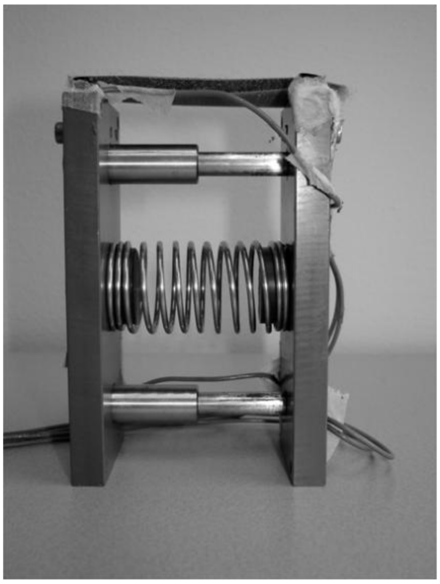


Figure 4.2 *One of the deformable objects, consisting of two plates with a spring in between and Velcro mounted on top.*

Procedure and Design

Tests

During the pretest prior to the learning sessions, SHAP was assessed to establish the baseline skill of the participants in both the experimental groups and the control group. After the last learning session, SHAP was administered again to determine the improvement of skills in the posttest. To determine the effect of learning over a longer period in the experimental group, two retention tests were assessed (see Table 4.1 for the experimental design). The control group only performed the first two SHAP tests, with the same time in between them as the pretest and posttest of the experimental group. This setup was chosen because SHAP is not validated yet for prosthesis users, and the control group served to examine the learning effect of performing SHAP twice.

Table 4.1 Set up of the experiment over the sessions

Pretest	S 1	S 2	S 3	S 4	S 5	Posttest	Retention test after 2 weeks	Retention test after 3 months
DG	DG	DG	DG	DG	DG	DG	DG	DG
IG	IG	IG	IG	IG	IG	IG	IG	IG
FIX	FIX	FIX	FIX	FIX	FIX	FIX	FIX	FIX
COM	COM	COM	COM	COM	COM	COM	COM	COM
CO	-	-	-	-	-	CO	-	-

S = session

Participants sat comfortably at a table, with their arms resting on the table and elbows in approximately 90 degrees, conform the SHAP manual. Prior to each task, task instructions were given. Different from the standardized SHAP protocol, the participants were not allowed to practice each task in advance to avoid premature learning during the pretest. The participants commenced each task with the prosthetic hand closed, and pressed a timer before and after executing each task for time measurement.

Sessions of the experimental group

During five sessions, spread out over a 2-week-period, participants learned the task(s) they had been assigned to (Table 4.1). Each session started with fitting of the prosthetic simulator, the LEDs and rigid bodies of the registration system. An Eyelink helmet (EyeLinkII, SR Research) was put on the head of the participants to measure gaze behavior of the participants. Prior to the start of the measurements, both Optotrak and Eyelink systems were calibrated. In this study, the results of the gaze data will not be reported, therefore we will not present details on that behalf.

For direct grasping, participants were instructed to pick up the object in front of them with the prosthetic hand, lift it, manipulate the object by pulling off the Velcro cover with the sound hand, and return it to the same position. The starting position of the prosthetic hand was located 15 cm from the edge of the table, and the object was located 30 cm distal from the initial hand position, both in line with the shoulder. During indirect grasping, the object was situated in the sound hand,

and participants were instructed to hand over the object to the prosthetic hand, manipulate the object and return it to the starting position of the prosthetic hand. The initial positions of the sound and prosthetic hand were 25 cm from the edge of the table opposite to each other in the frontal plane, with 30 cm distance between both hands. The middle between the hands was aligned with the body midline. For both grasping tasks, participants had to execute the tasks as quickly but as accurately as possible, without deforming the objects.

Four different tasks were administered during fixation. Participants had to fixate 1) a case with a flat design and zipper located at one side on top of the case, while unzipping and zipping the case with the sound hand; 2) a ruler on top of two dots—placed 20 cm horizontally from each other—with the prosthesis, while drawing a straight line between the dots with a pencil held in the sound hand; 3) a sharpener to sharpen a pencil by turning the handle of the sharpener 3 times with the sound hand; and 4) a piece of cloth to unbutton three buttons. The objects were placed on the force plate, 25 cm from the edge of the plate, aligned with the body midline. Participants were instructed to fixate the object with the prosthesis as still as possible during the task execution.

No further instructions were given for all three types of tasks (DG, IG, and FIX) to capture the natural developing changes in movement over time. The participants were informed that the spring stiffness's of the three objects differed, the stiffness was also marked on the object, however, they were not allowed to practice with the objects beforehand. Each session contained 60 trials for all groups. The DG, IG, and FIX group performed 15 trials with each of the 4 objects in a random order, resulting in 60 trials per session. The COM group performed 5 trials per object and per task (DG, IG, and FIX), resulting in 20 trials per task and thus 60 trials per session, with a randomized order of tasks (resulting in a blocked-repeated structure).

Data analysis

Analysis of tests

Time scores of SHAP were entered into the SHAP website[93], which provided an overall Index of Functionality (IoF) score. Apart from the IoF, the time scores of the tasks were analyzed separately to obtain more detailed information. The time scores were transformed to z-scores, which are normalized scores with a mean of 0 and a standard deviation of 1, enabling comparison of all tasks. Z-scores were calculated by subtracting each score, thus for each participant and for each task over all tests, from the mean of all scores, and then dividing the resulting score by the standard deviation. Further, mean z-scores were calculated for each type of task in SHAP: abstract light, abstract heavy, and ADL. Two repeated measures ANOVA's were executed on the mean z-scores; one to test the difference in performance between the experimental and control group with task type (abstract light, abstract heavy, and ADL) and test (pretest and posttest) as within-subject factors and group (experimental and control) as between subject factor; and the second to test the difference between tasks practiced in the sessions and the performance over a longer period, with task type (abstract light, abstract heavy, and ADL) and test (pretest, posttest, 2-weeks retention, and 3-months retention) as within-subject factors and group (DG, IG, FIX, COM) as between-subject factor. Three t-tests on the abstract light, abstract heavy, and ADL task types were executed on the pretest results to see whether the experimental group and the control group were equal in performance at baseline.

Analysis of the learning sessions data

The onset and termination of the dependent variables of the end-point kinematics in the grasping tasks were determined using the Multiple Sources of Information method introduced by Schot et al.[94] (see Table 4.2) that was implemented in custom written Matlab programs. Reach time and peak velocity of the reach were determined for the transport phase. Hand opening time, plateau time, hand closing time, total grasp time (see also Figure 4.4), maximal aperture, mean velocity of hand opening, and mean velocity of hand closing were calculated for the grasp phase. Grasp was defined by the 3D distance between the markers on the thumb and index finger. Synchronization at end, which reflects the timing of the end of the reach and the grasp, was computed by dividing the time of grasp termination by the time of reach termination. A score of 1 stands for simultaneous ending of the reach and grasp. When the grasp ended later than the reach, scores exceeded 1, and when the grasp ended before the end of the reach, scores were below 1. Compression of the object was calculated by computing the 3D distances between the two markers on the opposite ends of the object, and determined for two moments: maximal compression during the initial grasp and maximal compression during manipulation of the object. The applied force during the initial grasp (Force at moment of grasp) and during manipulation (Force during manipulation) was subsequently derived from the constant of each of the springs: F(N) = constant of the spring (N/mm) * compression of the object (mm).

The force data of the fixation tasks, sampled by the force plate, was processed using custom made Matlab programs. The force perpendicular to the force plate

(Fz) was used to determine maximal Fixation force during a trial. Fixation time was determined as the time that the applied force exceeded a threshold of 2 N.

Joint angles were calculated following the recommendations of the International Society of Biomechanics (ISB) proposed by Wu et al.[95, see also 92,96] The following angles were analyzed: flexion-extension, lateral bend, and rotation of the trunk; plane of elevation, elevation, and internal-external rotation of the shoulder; and elbow flexion-extension. Note that plane of elevation and elevation of the shoulder both determine the angle between the upper arm and trunk. Only the above mentioned trunk, shoulder and elbow angles at the side on which the prosthetic simulator was attached, were determined. Time of each movement was normalized (0-100%) to facilitate comparison. Range of Motion (ROM) for each angle was calculated by subtracting the minimum value from the maximum value of the angle in each trial.

The data were processed using Matlab (The Mathworks Inc, MA, USA). Trials were rejected when markers were obscured so that one or more of the above mentioned variables could not be determined. Repeated measures ANOVA's were applied on each of the dependent variables (reach time, hand opening time, plateau time, hand closing time, total grasp time, mean velocity of hand opening, mean velocity of hand closing, synchrony at end, compression at moment of grasp, compression during manipulation, force at moment of grasp, force during manipulation, fixation force, and fixation time) with session (session 1 to session 5) and object (LO, MO, HO, and solid for the grasping tasks; and case, sharpener, buttons and ruler for the fixation tasks) as within-subject factors and group as between-subject factor. When sphericity was violated, the degrees of freedom were adjusted with the Greenhouse-Geisser correction. An α of .01 was used because of the large number of analyses performed. Post hoc tests on main effects used Bonferroni corrections. Generalized eta-squared[60] was used to calculate effect sizes, and interpreted according to Cohen's recommendation[61] of .02 for a small effect, .13 for a medium effect, and .26 for a large effect. Only effects of .02 and larger are discussed in the results.

Table 4.2 The cut-off thresholds of the dependent variables for the end-point kinematics

Variables	Description	DG	IG
Start reach	X-position and Z-position of the hand on the table	90 < x-position hand < 150 mm	500 < x-position hand > 600 mm & z-position hand < 90 mm
	The hand is closed at the start	Aperture hand < 30 mm	Aperture hand < 30 mm
	Velocity of the hand starts to increase	10 < velocity hand < 50 mm/s	10 < velocity hand < 50 mm/s
End reach	The hand must be near the object	390 < x-position hand < 500 mm	0 < distance hand-object < 35 mm
	Velocity of the hand slows down	0 < velocity hand < 10 mm/s	0 < velocity hand < 20 mm/s
	Position of the object is not changed (only DG)	z-position object <87 mm	-
Start grasp	Aperture of the hand starts to increase	20 < aperture hand <50 mm	20 < aperture hand < 50 mm
	Velocity of hand opening starts to increase	Velocity hand opening > 20 mm/s	Velocity hand opening > 20 mm/s
End grasp	Aperture of the hand about size object	65 < aperture hand < 95 mm	65 < aperture hand < 95 mm
	Velocity of hand closing decreases to 0	0 < velocity hand closing < 15 m/s	0 < velocity hand closing <15 mm/s
	Grasp has ended as object starts to move (only DG)	84 < z-position object < 100 mm	-
	The hand must be near the objet	390 < x-position hand < 500 mm	0 < distance hand-object < 35 mm
Start Plateau	Aperture is around maximum	90 < aperture hand < 150 mm	80 < aperture hand < 140 mm
	Velocity of hand opening decreases to 0	0 < velocity hand opening < 20 m/s	0 < velocity hand opening < 0mm/s
	Position of object is not changed yet (only DG)	z-position object < 87 mm	-
End plateau	Aperture is around maximum	90 < aperture hand < 150 mm	80 < aperture hand < 140 mm
	Velocity of hand closing starts to increase	15 < velocity hand closing < 30 m/s	15 < velocity hand closing < 80 m/s
	Position of object is not changed yet (only DG)	z-position object < 87 mm	-

Results

Tests

The participants in the experimental group improved from a mean Index of Functionality (IoF) score of 35.61 on the pretest to 55.52 in the posttest (Figure 4.3). The performance remained on the same level during the retention tests, with a IoF score of 58.16 on retention test 1 and 58.58 on retention test 2. The control group improved as well from the first to the second test (mean = 43.87 and 52.87, respectively; see Figure 4.3). Three t-tests confirmed that the control group and the experimental group did not differ significantly from each other at baseline (t = .22, p = .83 for the abstract light tasks; t = -.50, p = .62 for the abstract heavy tasks; and t = 1.61, p = .11 for the ADL tasks).

Although the ANOVA on the z-scores showed that both the experimental group and the control group improved on SHAP ($F_{(1,59)}$ = 153.18; p = .00; η_G^2 = .33), an interaction-effect of test by group revealed that the experimental group improved significantly more on the posttest compared to the control group ($F_{(1,59)}$ = 21.61; p = .00; η_G^2 = .07).

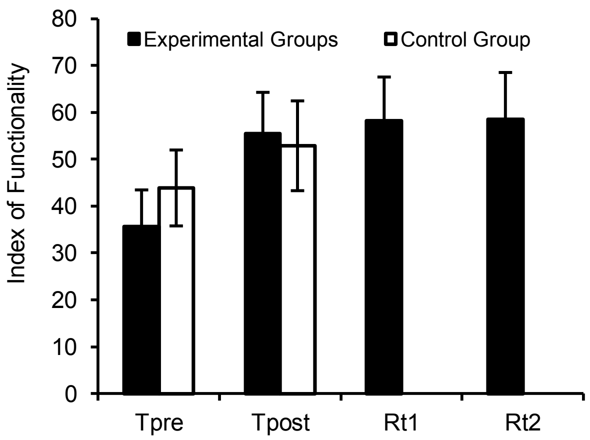


Figure 4.3 *Mean (SD) Index of Functionality scores on SHAP for the experimental and the control groups on the different test times: pretest (Tpre), posttest (Tpost), retention test 1 (Rt1), and retention test 2 (Rt2).*

A large effect of test ($F_{(1.37, 37.02)}$ = 93.19; p = .00; η_G^2 = .49) showed that, within the experimental group, participants improved significantly on both the posttest and the retention tests compared to the pretest (p's = .00 in pairwise comparison). The participants improved most on the light-weight abstract tasks over the time, revealed by a small interaction-effect of test by task ($F_{(2.64, 71.40)}$ = 4.75; p = .01; η_G^2 = .03). The four experimental learning groups did not differ significantly from each other.

Learning sessions

Grasping tasks - kinematics and applied grip force

Figure 4.4 shows a typical profile of the performance during a direct grasping trial. During the approach phase, the hand reaches towards the object. In the reach the hand opens to a maximal hand aperture, stays at a plateau for a while, and starts to close when the hand is near the object. During the grasp phase the object is picked up, and two types of compression of the object can be determined. The first compression occurs immediately when the object is picked up, and the second—further—compression occurs when the Velcro strip is pulled off.

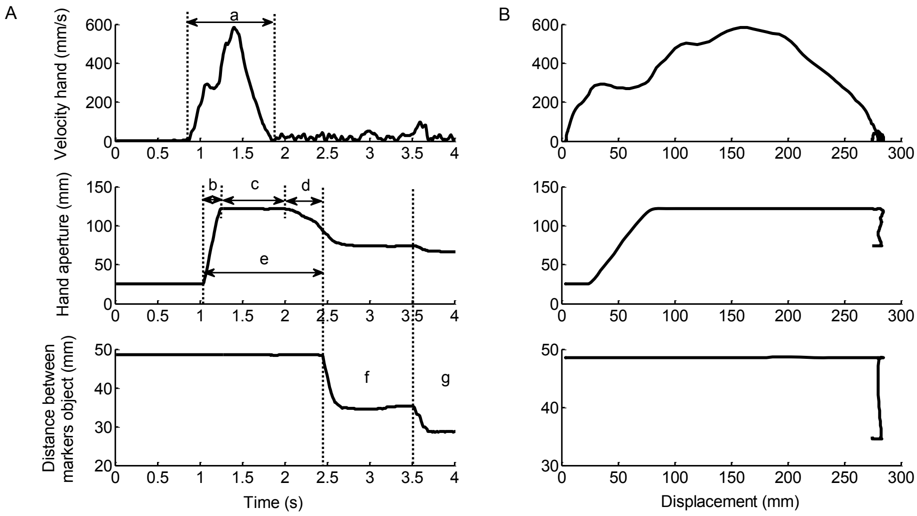


Figure 4.4 *Illustrative samples of a direct grasp trial with the low-resistance object. Velocity of the hand, hand aperture, and object deformation are plotted against time (A) and against displacement of the hand (B). Several dependent variables are indicated in 4A: a = Reach time; b = Hand open phase; c = Plateau phase; d = Hand close phase; e = Total grasp time; f = Compression during grasp; g = Compression during manipulation.*

Table 4.3 provides an overview of the mean (M) and the standard error (SE) of all significant main effects with an effect size of ≥.02. A main effect of session shows the means of each of the five sessions, calculated over the objects and over the groups, while a main effect of object shows the means of each of the objects, calculated over the sessions and over the groups.

During the five sessions, a decrease was seen in the reach time, the plateau time, and the total grasping time, mainly on the first three sessions (Table 4.3). Moreover, although not significant, a gradual decrease throughout the five sessions was seen in the amount of compression of the object and therefore in the amount of grip force applied during grasping (M (SE) for session 1: 4.68 (.38); session 2:

4.29 (.24); session 3: 4.08 (.21); session 4 (3.24 (.17); and session 5 3.12 (.14)) and manipulation (M (SE) for session 1: 5.60 (.45); session 2: 4.95 (.25); session 3: 5.03 (.24); session 4: 4.12 (.19); and session 5: 3.87 (.16)), which did not show leveling off. No significant main effect of group was found.

An interaction effect of session by group in the compression during grasp ($F_{(4.8, 69.9)} = 3.22$; $p = .01$; $\eta_G^2 = .03$) revealed that both the DG and COM group compressed the objects less over the sessions, while the IG group did not show this decrease in compression (Figure 4.5A).

With a low resistance of the object, thus with the object that was easier to compress, the plateau time, the hand closing time, and the total grasp time increased, whereas synchronization of the end of the reach and grasp and the mean velocity of hand closing decreased. The objects with low resistance resulted in larger compressions during grasp and manipulation of the object compared to the HO, while force production was less with the lower object resistances (Table 4.3).

Small interaction effects of group by object in hand closing time ($F_{(3.4, 49.9)} = 6.27$; $p = .00$; $\eta_G^2 = .04$), total grasp time ($F_{(4.2, 61.3)} = 7.63$; $p = .00$; $\eta_G^2 = .04$), and nearly significant synchrony at end (p = .03) revealed that a higher object stiffness resulted in a faster performance in the DG and COM groups, while the performance of the IG was about equal for the four objects (Figure 4.5B). Note that the performance of the IG group was overall faster than the other two groups. Nearly significant interaction effects of group by object for compression during grasping ($p = .04$) and compression during manipulation ($p = .02$) revealed that overall, the groups adjusted the performance to the characteristics of the objects, however, the IG group compressed the LO somewhat less than the DG and COM groups. The mean velocity of hand closing increased over increasing object stiffness ($F_{(3.3, 48.4)} = 4.43$; $p = .01$; $\eta_G^2 = .03$), where the IG group showed the overall fastest velocities for the LO, MO, and HO objects, while the COM group closed the hands the fastest for the solid object.

Fixation tasks – applied fixation force

The maximal fixation force used differed largely per object (Table 4.3), indicating that participants could adjust the fixation force as needed to finish the task. A small interaction effect of session by object ($F_{(12,72)} = 3,16$; $p = .01$; $\eta_G^2 = .03$) revealed a different fixation performance over the five training sessions, with slightly increasing maximal fixation force for the case, sharpener, and ruler over the sessions, whereas the maximal fixation force slightly decreased for the buttons task.

Table 4.3 Significant main effects in the learning sessions with an effect size of ≥ .02

Dependent variable	**Within/ between subject factor**		**Mean (SE)**	**95% CI Lower-Upper**	**F**	***p***	η_G^2
Reach time (s)	Session	1	1.49 (.07)	1.36-1.63	5.66	.00	.03
		2	1.36 (.05)	1.25-1.47			
		3	1.33 (.05)	1.23-1.44			
		4	1.36 (.05)	1.26-1.47			
		5	1.35 (.06)	1.23-1.47			
Plateau time (s)	Session	1	0.93 (.06)	0.82-1.04	10.43	.00	.05
		2	0.75 (.05)	0.65-0.85			
		3	0.72 (.04)	0.64-0.81			
		4	0.78 (.05)	0.68-0.88			
		5	0.78 (.05)	0.69-0.88			
	Object	LO	0.84 (.04)	0.76-0.93	11.66	.00	.02
		MO	0.83 (.05)	0.73-0.93			
		HO	0.77 (.04)	0.69-0.86			
		Solid	0.73 (.05)	0.63-0.82			
Hand close time (s)	Object	LO	0.79 (.06)	0.68-0.91	35.72	.00	.11
		MO	0.73 (.05)	0.62-0.83			
		HO	0.57 (.05)	0.48-0.69			
		Solid	0.49 (.04)	0.41-0.57			
Total grasp time (s)	Session	1	1.98 (.11)	1.75-2.21	8.66	.00	.03
		2	1.72 (.10)	1.51-1.92			
		3	1.67 (.08)	1.51-1.83			
		4	1.77 (.09)	1.59-1.95			
		5	1.77 (.09)	1.58-1.95			
	Object	LO	1.99 (.09)	1.79-2.18	32.54	.00	.07
		MO	1.89 (.09)	1.69-2.09			
		HO	1.68 (.09)	1.50-1.86			
		Solid	1.56 (.09)	1.38-1.74			
Mean closing velocity (mm/s)	Object	LO	84.95 (5.87)	72.95-96.95	13.48	.01	.04
		MO	86.02 (6.25)	73.24-98.80			
		HO	86.64 (6.40)	73.55-99.73			
		Solid	109.42 (8.81)	91.40-127.44			
Synchrony at end	Object	LO	1.55 (.04)	1.46-1.64	20.19	.00	.08
		MO	1.51 (.04)	1.42-1.59			
		HO	1.43 (.04)	1.35-1.51			
		Solid	1.34 (.03)	1.27-1.41			
Compression at moment of grasp (mm)	Object	LO	10.09 (.84)	8.36-11.82	131.35	.00	.47
		MO	10.20 (.62)	8.93-11.47			
		HO	1.38 (.21)	0.96-1.81			
Compression during manipulation (mm)	Object	LO	13.22 (.98)	11.21-15.22	166.78	.00	.54
		MO	12.53 (.63)	11.25-13.82			
		HO	1.74 (.23)	1.27-2.21			
Force at moment of grasp (N)	Object	LO	1.73 (.15)	1.43-2.02	27.12	.00	.19
		MO	5.81 (.35)	5.09-6.54			
		HO	7.34 (1.09)	5.11-9.58			
Force during manipulation (N)	Object	LO	2.26 (.17)	1.92-2.61	32.67	.00	.22
		MO	7.14 (.36)	6.41-7.88			
		HO	9.21 (1.22)	6.72-11.70			
Fixation force (N)	Object	Case	41.33 (3.45)	33.14-49.52	25.31	.00	.53
		Sharpener	45.32 (3.20)	37.21-52.85			
		Buttons	30.22 (4.35)	19.58-40.85			
		Ruler	19.80 (1.82)	15.36-24.25			
Fixation time (s)	Object	Case	4.97 (.67)	3.34-6.60	15.18	.00	.28
		Sharpener	5.57 (.87)	3.43-7.71			
		Buttons	6.83 (.50)	5.62-8.04			
		Ruler	9.06 (.90)	6.87-11.25			

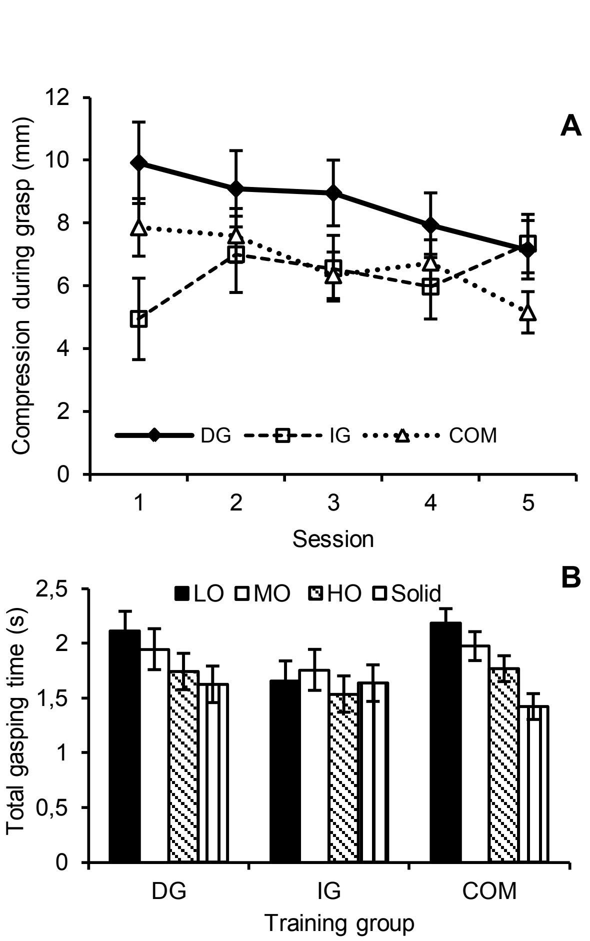


Figure 4.5 *A) The amount of compression of the objects over the sessions for each of the training groups that trained grasping (DG, IG, and COM); B) Total grasping time for each of the training groups for the different object resistances LO, MO, HO, and solid.*

Although it did not reach significance, the fixation time decreased over the sessions of practice (p = .03; mean session 1: 8.78, session 2: 6.42, session 3: 6.43, session 4: 5.85, session 5: 5.55), and the time needed to fixate the objects differed largely (Table 4.3). Participants performed the case task the quickest, followed by the sharpener and the buttons, and the ruler task took most time. No differences were found between the FIX and COM group.

Joint angles in grasping and fixation tasks

The mean range of motion (ROM) and the standard deviation of the ROM of the shoulder, elbow, and thorax decreased mainly from the first to the second session. Figure 4.6 shows the angles of the shoulder, elbow, and thorax on the first and the fifth session. Overall, the ROMs were the highest for the fixation tasks, and the lowest for the IG task. The fixation tasks required the highest abduction angles—reflected by the lowest degree in plane elevation where 0° is abduction and 90° is forward flexion of the arm. All tasks were performed with the thorax in some forward flexion, lateral flexion to the left—away from the prosthesis side—and some left rotation. Over the sessions the lateral flexion and rotation of the thorax decreased to zero.

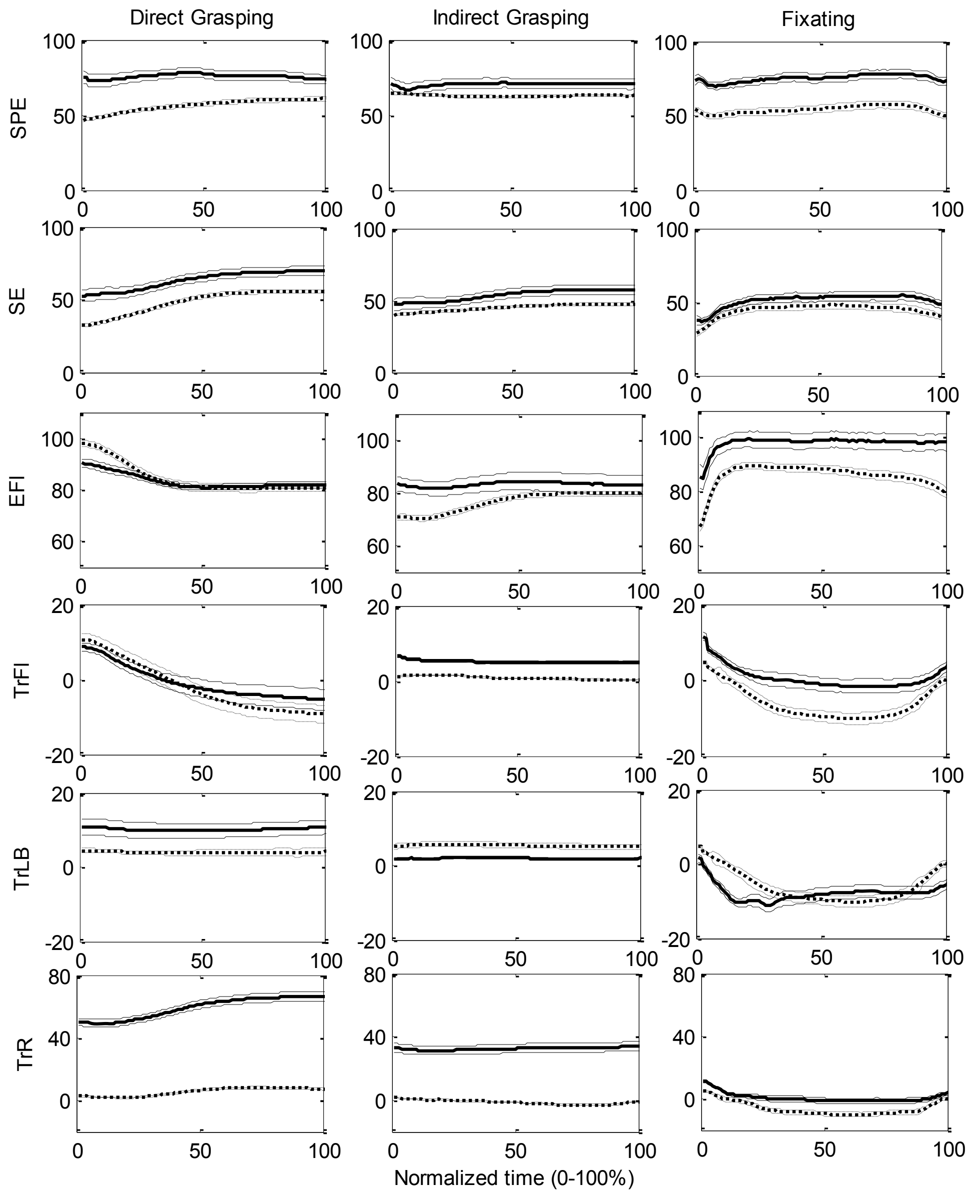


Figure 4.6 *The mean course in angles (degrees) of shoulder plane of elevation (SPE), shoulder elevation (SE), elbow flexion (EFl), thorax flexion (TrFl), thorax lateral bend (TrLB), and thorax rotation (TrR) from movement start to end in normalized time for the three types of tasks (direct grasping, indirect grasping, and fixating). The solid lines represent the mean and standard error of angles on the first session, the dashed lines represent mean and standard error for the fifth session.*

Discussion

Improvement over practice time

All groups improved on SHAP in the posttest, with a significantly larger improvement in the experimental groups compared to the controls. This implies that practicing with the prosthetic simulator improved overall performance, hence, not only familiarization to the task as the control group experienced but training is necessary to increase skills in prosthesis use. Moreover, the performance did not deteriorate in the retention tests. This is interesting, as it shows that the improvement is lasting, even after a period of non-use of the prosthesis. For movement times in the end-effector kinematics, fixation time, and range of motion, a fast improvement was seen between the first and second session, after which the improvement decreased over the next sessions and leveled off after three sessions. The learning process of the force control proceeded differently. Although not significant, the improvement in performance over the five sessions demonstrated an ongoing improvement in the learning process without leveling-off. These results make clear that controlling the hand, especially the fine-tuning of adjusting the opening and closing to different object characteristics, which reflect fine motor control[97], takes longer to learn than the gross motor control such as the positioning of the prosthetic arm in the surrounding space. This is not surprising, however, if one recalls that the joints and muscles around the shoulder and elbow are still intact and also used for these gross motor actions when using a forearm prosthesis. Therefore it is likely that, as also suggested by Metzger et al.[24], the existing sensory feedback in shoulder and elbow provided enough information to learn to control such movements quickly. On the other hand, the prosthetic hand has replaced the own hand, and needs to be controlled with the muscles that first mainly controlled the wrist instead of the hand. It is reasonable to presume that this results in a longer period to master control of the hand.

Differences between experimental groups

During the learning sessions, the different tasks led to a difference in performance of the groups. Whereas the DG and COM improved over the sessions and adjusted the control of the hand to the characteristics of the objects, this was not seen in the IG group. Notice, however, that the IG group started off better and had an overall better performance; they were overall faster than the other two groups, and compressed the object with the low resistance less. The difference in performance could be explained in several ways. One of the reasons might be that during the IG task, more information can be retrieved about the deformable objects because of the involvement of the sound hand. This bimanual component in the indirect grasping included proprioception of the sound hand, which could have led to a better translation to the control signals of the prosthetic hand. Moreover, the participants were able to position the object with the sound hand into the prosthetic hand. Therefore, unlike the DG task, no attention had to be paid to positioning of the prosthetic hand with regard to the position of the object. Finally, the absence of improvement in IG group over the sessions could also have resulted from their relatively good start, which might have left no room for improvement. This finding is important, since amputees need to achieve success when they start practicing with a prosthesis, to motivate them to continue practicing and to use the prosthesis. Therefore, we recommend to start with an IG task.

Even though the number of repetitions during practicing each individual task was less, the level of performance of the COM group in the functional test was equal to the other groups. Hence, less practice of each task in this group led to comparable results, which means that they have learned more in less repetitions. The advantage of the COM group was that they were able to use the information obtained during IG while performing DG, which might have helped to improve overall performance. Together with the blocked-repeated order of tasks in which they learned, there results could suggest that this particular structure of learning might lead to the best overall performance over time. Learning in a random manner—with several tasks learned at the same time—has been shown to lead to the best transfer of skills to other tasks than learned.[98,99] The blocked-repeated fashion that is used in this study has been suggested as the best training design to achieve the best overall performance.[63,100]. This allows learning a task quickly while practicing it in a blocked order for several repetitions, whereas the repetition of these blocks would promote transfer of the skills.

The fact that all experimental groups performed equally on the SHAP tests after training is a finding that deserves attention. Especially the performance of the fixation group is remarkable. These participants only fixated objects during the learning sessions and did not learn to control the prosthetic hand actively, while SHAP tasks require active control of the hand. At the moment, we cannot provide a conclusive explanation for this lack of difference between the groups. What was noticed during the sessions, however, was that the prosthetic hand was often—unintentionally—opened during fixation, and participants had to close the hand again in order to start the next trial. This could imply that they did practice active control of the hand to some extent, and were therefore able to perform the SHAP tasks that required active control of the hand. The equal performances of the four training groups could suggest that experience and practice with the prosthesis in itself could provide enough training; however, we might expect that with longer training that has more specific feedback about hand control, differences between the groups could emerge.

Improvement in grip force control

The participants were able to learn force control over practice sessions, with a gradual learning process that we expect to have continued when we had measured over an even longer period of time. As overall grip force decreased over the sessions, the participants were also able to adjust the control of the hand according to characteristics of the objects. The results demonstrate that with a prosthetic hand control of grasping force takes a long time, implying that it needs special attention and training to avoid crushing objects.[9]

The fact that force control can be learned with a prosthetic hand has been reported earlier[101-104], however, this study is the first using compliant objects during goal-directed grasping tasks over a period of time, providing supplementary information on prosthesis control where other studies have only used rigid setups or non-goal-directed functional tasks to measure force control. It is surprising though, that most of the prehension research and control of the hand—both with sound hands and prosthetic hands—has been performed with rigid objects[105], since many objects are deformable in daily life. Interesting from the rehabilitation perspective is the fact that participants, relying solely on visual feedback because the prosthetic hand lacks the sensory information that is present in sound hands, were able to learn to control the force applied by the prosthetic hand. Thus, the still existing visual feedback provided enough information to learn force control to a certain extent. Since feedback plays a central role in motor learning[82,83], it is of interest to explore the role of feedback during the learning processes of learning to use a prosthesis further. Moreover, it is important to examine the relevance of providing augmented feedback such as visual feedback, auditory feedback, vibrotactile feedback or verbal feedback[106-108] during learning, especially while using the prosthesis handling compliant objects.

Understanding underlying motor learning processes

A question that arises from this study is whether our results could provide insight in the understanding of motor learning and motor control. The results of the current study exposed the changes in performance over time. Moreover, the results indicate that there are different processes involved when learning to use a prosthesis, shown by the results on the different outcome measures that were analyzed. One of the approaches to motor learning that could be applied to these results is the dynamical systems theory.[84] The dynamical systems approach examines changes in the movement organization—and thus in performance—and the interaction between the learner and the environment at multiple levels of analysis that each have their own changing time scales.[84,109] The learner self-assembles the information that is available to learn organizing the movements to achieve the desired outcome.[84,109] It seems that without having proprioceptive feedback from the prosthetic hand, the remaining information was sufficient to learn movements to a certain extent. Gross positioning could be learned rather well because of the information that is left in the remaining arm, while fine control takes more time, possibly because of the reduced information that is available, as the learners could only feed on the still existing visual feedback. This is reflected in the different changing time scales of learning observed in the study. The learning curve observed in the gross movements—which is similar to curves found in most learning studies, c.f. Newell[84]—is different from the fine control learning curve, which seems to have another, slower changing time scale. The dynamical systems approach could be an interesting approach to model the learning and performance of a prosthesis user, and to be able predict changes in future learning.

The dynamical systems approach comes forth from the work of Bernstein[1] who described the process of skill acquisition as learning to control the various degrees of freedom of the body. A human has many degrees of freedom of movement, although there are less when using a prosthesis, however, there are still redundant possibilities to achieve a desired outcome. One of the core questions in motor learning is how a learner finds the correct solutions to achieve a certain goal.[110] The process of finding the correct solutions has been examined by studying the variability over learning, which is a characteristic that is reported in many motor learning studies.[84,111-113] While the current study was set up to get a global picture of the changes in performance over time, a next step would be to take a more closer look at these processes of change of the different learning curves, by examining the variability of performance over practice. Applying a method such as the Uncontrolled Manifold[114,115] or the tolerance-noise-covariation (TNC) method[111,113] would be very informative to use, since it decomposes variability into several components, which will provide more detailed insight in how to promote learning the most.

Study limitations

The participation of able-bodied individuals using prosthetic simulators instead of amputees using real prostheses is a limitation of the study. The reason that we chose for this set-up is that there are only a very limited number of novice prosthesis users, and by studying able-bodied participants with a simulator many more subjects could be included. Moreover, it would not be ethical in this stage to deny novice prosthesis users the regular occupational therapy to be able to study the learning process in this set-up. Furthermore, comparing the current results to previous results provides indications that the use of the simulators are comparable to real prosthesis use in terms of SHAP scores[116,117] and kinematic profiles.[75,41,42,117] Therefore, the use of simulators seems to be justified. Another limitation might be that the control group was assessed only twice, during the pretest and posttest, but not during retention tests. We chose for this design because SHAP is not validated yet for prosthesis use and we deviated from the standard SHAP protocol. With hindsight, it might have been more appropriate to have measured the control group during retention tests as well.

Another factor that could be included in future research is the amount of mental effort that is required when learning to use a prosthesis. In the first part of the rehabilitation process a great amount of mental effort is required to learn to control the prosthesis. We expect that over learning the amount of mental effort will decrease, especially with the suggestions for clinical practice that emerged from this research. When mental effort is included in the outcome measures it would enhance our understanding further about how people learn to use their prosthesis, and in addition it might help us to determine the level of functioning of a prosthesis user during rehabilitation. This might be particularly true for learning grip force control because it takes a long time. Moreover, although we showed that grip force control can be learned it is unclear how these skills transfer to objects of different stiffness than practiced. It might be that mental load increases relatively a lot when objects of different stiffness need to be picked up. Future research is required to establish this because this is not explicitly tested in SHAP.

Clinical application

The set-up of this study approaches a rehabilitation setting more than a single time measurement design, which leads to useful clinical insights. First, when designing an evidence-based training, more time should be spend on force control compared to gross movements with prosthesis, since learning grip force control requires much more time and attention. Second, patients should start to train with at least an indirect grasping task, thereby increasing the amount of useful information provided by the sound hand to perform the task. This information can then be used for other tasks as well, as seen in the COM group. Third, patients should train in a blocked-repeated fashion, allowing quick learning of a specific task in one block, and promoting transfer of skills by variable repetition of the blocks as well.

Conclusion

Learning processes were examined in participants that learned to use a prosthetic simulator in different goal-directed tasks. Results showed that grasping force control took longer to learn than positioning of the prosthesis and that indirect grasping was beneficial for controlling the grip force. Practicing different tasks improved grasping control to the same level than training just grasping while the number of grasping trials in practice were less. Improvement in performance lasted even after a period of non-use. Suggestions for clinical practice are to focus specifically on grip force control of the hand, to start to train with an indirect grasping task, and to train in a blocked-repeated fashion.

Competing interest

This study was performed while Hanneke Bouwsema was financially supported by Otto Bock Healthcare GmbH, Vienna, Austria. By legal contract Otto Bock had no influence on the interpretation of the results and the wording in the manuscript.

Authors' contribution

HB participated in designing the study, conducted the experiment, performed the analyses, and drafted the manuscript. CS participated in designing the study and helped to draft the manuscript. RB participated in designing the study, participated in performing the analyses, and helped to draft the manuscript. All authors read and approved the final manuscript.

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5

Effect of feedback during virtual training of grip force control with a myoelectric prosthetic hand

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Submitted

Abstract

The aim of this study was to determine whether virtual training improves grip force control in prosthesis use, and to examine whether augmented feedback facilitates learning. Thirty-two able-bodied participants trained grip force with a virtual ball-throwing game for five sessions in a two-week period, using a myoelectric simulator. They received either feedback on the outcome or feedback on the movement execution. Sixteen controls received training that did not focus on force control. Variability over learning was examined with the Tolerance-Noise-Covariation approach, and the transfer of grip force control was assessed in a pretest, a posttest, and a retention test. During training, performance increased while the variability in performance was reduced, mainly by reduction in N-cost. Grip force control only improved in the test-tasks that provided information on performance. Feedback on the outcome enhanced transfer of grip force, while too much feedback was detrimental to learning, as well as starting with a task that required low grip forces. During rehabilitation, grip force training should start with tasks that allow high forces. Virtual environments should be carefully designed in terms of provision of information. Learning might be most effective when practicing tasks with and without feedback on performance, which might only be provided on the outcome of the movement to facilitate grip force control.

Introduction

To use an upper limb prosthesis dexterously, one needs training.[9,70,118] An evidence-based training should optimally facilitate skill acquisition, thereby enhancing functionality and efficiency with a prosthesis during training, and promoting transfer of skills from training to everyday life situations. Learning to use a prosthesis implies that motor learning takes place, which is generally seen as the permanent changes in behavior as result of practice.[21] Practice is therefore one of the most important factors in motor learning as the degree of improvement depends on the amount of practice.[21,119] Another factor that has effect on the motor learning process is feedback.[119] With provision of the correct augmented feedback during or after practice, learning can be maximally enhanced.[88,120] In this study, we examined the influence of feedback on the learning process while training with a myoelectric prosthesis. Revealing those motor learning processes of prosthesis users allows designing evidence-based training protocols that optimize these learning processes. Therapists could benefit from such protocols to enhance prosthesis skills.

When one learns a new skill, the performance is characterized with variability at the start that decreases with practice.[1,84,111,113] The type and degree of variability is an outcome measure that might help us to understand motor learning strategies of prosthesis users. Especially in redundant systems different types of variability can be distinguished.[84,111,113,114,121] Redundancy arises when there are more elements than necessary to create an action.[1,121] For example, the many elements of the human body have numerous degrees of freedom, which results in many different ways in which an action can be performed successfully. Although prostheses have less degrees of freedom than a human arm, this is also the case in prosthesis use. Therefore, studying the change in variability over learning while executing a task with redundancy might provide insight in how certain task solutions (i.e., movements) are chosen from a larger set of possible task solutions. In order to understand how prosthesis users learn to perform certain tasks, it is therefore informative to look at the change in variability over time during learning.

One of the methods to analyze performance in a task with redundancy is the so-called TNC analysis (Tolerance, Noise, Covariation), introduced by Müller and Sternad.[113] They developed a method that divides variability into three different components of variability, Tolerance (T), Noise (N) and Covariation (C). The method not only takes the end result (i.e., the outcome of the performance) into account, but also the execution variables (i.e., how the movement is performed), which is different from most other learning studies that look only at the outcome of performance. Müller and Sternad asked participants to hit a skittle with a ball by controlling two execution variables, angle and speed of the ball at the time of release. Different combinations of the angle and speed resulted in a successful solution, creating redundancy in the task. The end result of the performance was the error of the position of the ball with regard to the skittle. They described the variability in the end result as the sum of the three components, T, N, and C, which all contributed to improvement in the task performance. The task was more tolerant when many adjacent combinations of angle and velocity led to a successful solution. Noise was reflected in the random variation of performance, and covariation showed how various combinations of angle and velocity resulted in the same end result.[111,113] In this study, the TNC approach is used to study the learning of grip-force control with myoelectric prostheses. Novice prosthesis users performed a virtual ball-throwing task with a handle that acted as a joystick, grasped with the prosthetic hand. They could control two variables, angle and speed of the ball at the time of release, controlled by the angle of the handle and the applied grip force. Three aspects were investigated with this virtual task. First, the performance over learning was examined by analyzing the variability in performance with the TNC approach. Second, the influence of feedback on performance was examined, and the third aspect that was investigated was the level of grip force control that was learned as a result of the training.

Applying the correct amount of grip force is one of the most difficult aspects in dexterous handling of a prosthetic hand, because of the limited intrinsic feedback a prosthesis provides.[106,122-124] Despite many attempts to replace the lost sensory feedback[104,106-108], artificial feedback is still not applied in commercial available prostheses because its functioning is not yet optimal.[125-127] The feedback that is available to control actions with a prosthesis is visual information[103,128,129], which will therefore be the focus in this study. It is known that able-bodied persons can use visual information to predict motor control, based on the knowledge of object characteristics.[130-133] Despite the limited proprioceptive feedback, a certain level of the control of grip force has also been shown in studies with neurological patients as well as with prosthesis users.[90,91,104,107,117,134-137] Therefore, we expected that with the provision of the correct type of visual feedback during training, acquisition of grip force control can be optimally facilitated during training, and, more importantly, transfer of the grip force control will be promoted to performance after training. This is of particular importance for a dexterous use of the prosthesis in daily life.

Augmented visual feedback can easily be provided via virtual training systems, which is becoming increasingly popular (Anderson et al.[138] and Dawson et al.[139] provide an overview on studies on virtual training employed in the field of prosthetics). In this study, two types of feedback that are generally used in training, feedback on the outcome and feedback on movement execution, are presented during training in the virtual environment. Feedback on the outcome often leads to improved performance after learning in other tasks than trained.[21,140,141] Feedback on movement execution can lead to better performance during learning, demonstrated in particular in neurological patients[142], however, some studies show that performance might deteriorate if the feedback is not available anymore after learning.[143] It is not known which of these two types of feedback facilitate grip force learning and transfer of the skill; therefore, both types of feedback were examined in the virtual training. Although virtual reality training has shown positive effects on motor learning during training in some studies[144,145], to our knowledge there has not been a systematic study to date that proves learning of prosthetic skills and transfer of those skills to other tasks than trained.

Therefore, the aim of the present study is to determine whether virtual training improves force control in prosthesis use, by examining the variability over learning, and to examine whether virtually provided augmented feedback facilitates learning. We hypothesized that 1) performance will increase during learning; 2) variability will decrease over learning; 3) feedback on the outcome will enhance transfer of learning more than feedback on the movement execution; and 4) grip force control will improve as a result of the virtual force training.

Methods

Participants

Thirty-two able-bodied participants received force control training (11 males, 21 females; mean age (SD) 21.28 (3.21) years), randomly assigned to either a group that received feedback about the outcome—the landing position of the ball (LF)—or feedback about the movement execution—the applied parameters angle and force, and the trajectory of the ball (TF). Another sixteen able-bodied participants received training that did not focus on force control (CO; 9 males, 7 females; mean age (SD) 21.56 (2.71) years). All participants were right handed, had normal vision, and had no earlier experience with a myoelectric prosthetic simulator (see Materials). The local medical ethics committee (NL40721.042.12) approved the experiment. Before the start of the experiment, participants signed an informed consent form. They received a gift voucher at the end of the experiment.

Materials

Participants wore a myoelectric prosthetic simulator to mimic a below-elbow myoelectric prosthesis. The simulator was developed to closely resemble a real prosthesis. See our earlier work[75,118,146] for further details on the prosthetic simulator and the procedure of donning the simulator.

The experiment was executed with a custom-made program on a laptop (created with Labview; display and sample frequency 100 Hz). A handle, comparable with a joystick, was used to execute the tasks (see Figure 5.1 for the experimental setup). The handle was equipped with a force transducer (LLB350 Loadcell (Futek); maximum force 222 N) and an electrical resistance meter (resistance value ranged from 0KOhm to 10KOhm in an angle from 0-360 degrees) to measure the applied force and the angle of the handle, respectively. The handle could be moved only in one plane, parallel to the table.

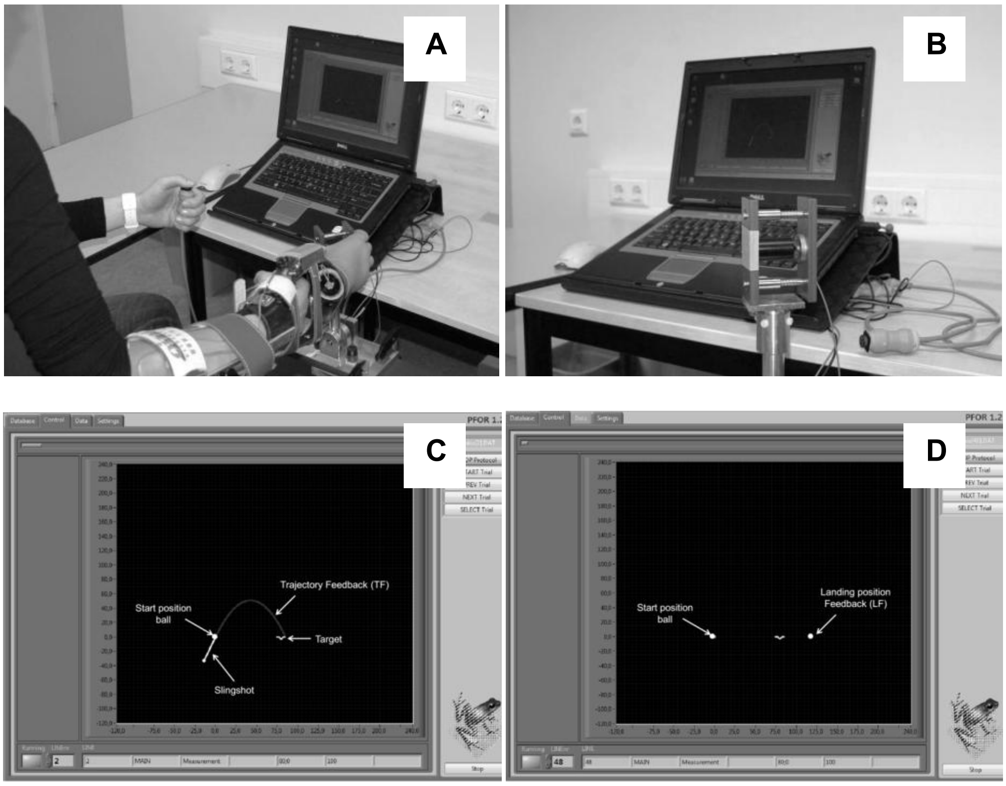


Figure 5.1 *Experimental setup; a participant in action with the prosthetic simulator attached to the right forearm, controlling ball release by pressing a button with the left hand (A), the measurement setup with the handle (B), and two screenshots of a thrown ball with trajectory feedback (C) and with landing position feedback (D).*

Three deformable objects were used, consisting of 2 plates (6 cm x 3.5 cm x 9 cm) with a spring in between (Figure 5.2), to simulate objects used in daily life such as a milk carton. Each object had a spring with a different constant; a low-resistance object (LO; c = 0.17 N/mm), a moderate-resistance object (MO; c = 0.57 N/mm) and a high-resistance object (HO; c = 5.31 N/mm).

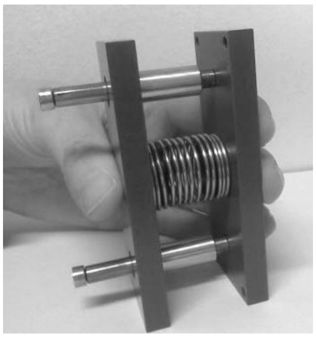


Figure 5.1 *One of the deformable objects consisting of 2 plates with a spring in between.*

The Box and Blocks Test[147] was used to train the CO group. The test was modified for the training purpose, with only 30 blocks instead of 150 and was performed standing instead of sitting. A laptop with a running stopwatch provided the participants with visual feedback about their performance times.

Design and procedure

Five test-tasks were assessed that tested different aspects of force control. These test-tasks were applied before (pretest) and after training (posttest) and in a retention test, which was administered two weeks after the posttest. The training consisted of five sessions in which the LF and TF participants trained a virtual force control task, while the CO participants trained with the Box and Blocks Test. The sessions were spread out over a period of two weeks to mimic a rehabilitation setting, in which training is also spread out over a longer period. See Table 5.1 for an overview of the experimental design.

Virtual force training

Participants played a virtual ball throwing game in which they had to throw a ball with a certain angle and velocity into a target. The ball was presented left, attached to a slingshot-spring (c = 1 N/m) that was shown as a white line. The velocity of the ball was determined by the degree of elongation of the slingshot, which in turn was controlled by the force applied to the held object. The more force applied, the longer the slingshot, with a range of 0-100 N. The angle of ball release was controlled by rotating the handle (range 0 to 90 degrees). After selection of the force and the angle, the ball was released by pressing a button, held in the

Table 5.1 Overview of the experimental design

Session 1				**Session 2**			**Session 3**			**Session 4**			**Session 5**				**Session 6**
Day 1 – Monday				**Day 3 – Wednesday**			**Day 5 – Friday**			**Day 9 – Tuesday**			**Day 11 – Thursday**				**Day 25 – 2 weeks after posttest**
Pretest	Training 1			Training 2			Training 3			Training 4			Training 5			Posttest	Retention test
Group	FB	TD	Trials	FB	TD	Trials	FB	TD	Trials	FB	TD	Trials	FB	TD	Trials	Group	Group
LF	LF 20-120	20	75	LF 20-120	80	60	LF 20-120	40	45	LF 20-120	100	30	LF 20-120	60	15	LF	LF
		80	15		40	30		100	45		60	60		120	75		
	LF 120-20	120	75	LF 120-20	60	60	LF 120-20	100	45	LF 120-20	40	30	LF 120-20	80	15		
		60	15		100	30		40	45		80	60		20	75		
TF	TF 20-120	20	75	TF 20-120	80	60	TF 20-120	40	45	TF 20-120	100	30	TF 20-120	60	15	TF	TF
		80	15		40	30		100	45		60	60		120	75		
	TF 120-20	120	75	TF 120-20	60	60	TF 120-20	100	45	TF 120-20	40	30	TF 120-20	80	15		
		60	15		100	30		40	45		80	60		20	75		
CO	BBTr			BBTr			BBTr			BBTr			BBTr			CO	CO

LF = Landing position feedback; TF = Trajectory feedback; CO = control; FB = feedback; TD = target distance opposing hand. The ball described a parabolic trajectory (see Appendix A for the formulas). Different combinations of angle and force resulted in a hit of the target, which created redundancy in the task.

Six targets were presented during five sessions with 90 trials in each session. The targets differed in x-position on the screen (20, 40, 60, 80, 100, and 120), while the y-position was always zero. Each target was practiced for 75 trials, thereby spreading the trials of the targets over the sessions, resulting in a transition between goals at different times within each session[113] to control for warm-up and retention effects. To control for the influence of target location, the two feedback groups (LF and TF) were split into two subgroups. Participants were randomly assigned to a subgroup that performed tasks in the order of 20-80-40-100-60-120 (LF 20-120 and TF 20-120), the other subgroup performed the tasks in the reverse order (120-60- 100-40- 80-20; LF 120-20 and TF 120-20).

The TF group received feedback about the executed movement: after each trial the elongation and position of the slingshot at the time of ball release and the trajectory of the ball were shown. The LF received only feedback about the end position of the ball.

Box and Blocks Training (BBTr): in each session, participants of the CO group performed the BBTr three times. They had to pick up and place 30 objects from one side to the other as fast as possible, which created a similar motivation as the grip force training group to perform as best as possible. The BBTr was chosen because it allows for practice with the prosthesis without training the force control explicitly. To provide visual feedback to this group as well, participants received feedback about the movement time, presented with a running stopwatch on a computer screen. Participants self-timed their performance by pushing the spacebar of a keyboard before and after transferring 30 blocks to start and stop the time.

Test-tasks

To test the ability of instant force production, the matching-test task was assessed. An amount of force was presented on the screen that the participants had to reach in one instant. The requested force (5 to 50 N in steps of 5 N, total of 10 trials in random order) was indicated by an orange marker on the screen. Participants were not allowed to adjust the force once they had produced a certain amount of force.

The tracking-test task assessed continuous force control. Participants had to track a pattern for 30 seconds that was displayed on the screen. The course of the pattern, indicated by a yellow line, appeared 200 ms before the red force signal produced by the participant. The yellow line always started with a flat line of 10 N for 3 seconds, after which the pattern started. Three different patterns were assessed; a sine wave, a blocked pattern and a compound sine wave (range of force 0-50 N). Each pattern was executed three times, resulting in 9 trials that were offered in blocked-random order. The range of force used in the matching and tracking test lies within the range needed to carry out activities of daily living.[148]

The picture-test task was used to assess how well participants could estimate the amount of force they had to apply when seeing a compressible object. Pictures of the MO and HO were shown on the screen, with a certain amount of compression (no compression, half compressed and totally compressed). Participants were instructed to provide the amount of force (to the handle) they thought was needed for lifting and compressing the object in that manner. Before the start of each trial, participants were allowed to experience the objects in real life with the normal hand. Each condition was repeated 2 times, resulting in 12 trials in random order.

The percentage-test task tested the ability to estimate the force applied with the prosthetic hand with regard to the maximum. First participants produced their maximum force. After that they had to produce a certain percentage of that force: 25%, 50%, 75%, in random order presented on the screen. Each percentage was repeated 3 times. No feedback was given about the performance.

Next to the four virtual test-tasks that were assessed with the experimental setup, a fifth test was included to assess performance in real life. In the object-test task participants had to pick up a compressible object with the prosthetic hand without trying to deform the object. Each object (LO, MO, HO) was assessed 3 times in random order, resulting in 9 trials.

Data analysis

Training

The angle, the amount of force produced and the x-coordinate of the end position of the ball were recorded for each trial. These outcome measures were used and analyzed with the TNC approach of Cohen and Sternad[111], using Matlab (Mathworks, R2012), to calculate the costs of the three components of variability, T-cost, N-cost, and C-cost. First, the error—distance to the target—was calculated. See Appendix A for the formulas used to calculate the trajectory of the ball and the error. The mean error of five blocks within each target, consisting of

15 trials, was first calculated per participant and then per group. A repeated measures ANOVA was executed on the error with target number (the number of practiced targets, i.e, number 1 to 6) and block (1 to 5) as within-subject variables and feedback (LF and TF) and target distance order (20-120 and 120-20) as between-subject variables. T-cost, N-cost, and C-cost were calculated following the description in the article of Cohen and Sternad.[111] To examine the performance of the different groups during training, three different repeated measures ANOVA's were executed on the three variables, T-cost, N-cost, and C-cost, with target number (number 1 to 6) and block (1 to 5) as within-subject variables and feedback (LF and TF) and target distance order (20-120 and 120-20) as between-subject variables.

Mean time and standard deviation of performance on the BBTr was calculated over all control participants for each of the trials in the five sessions.

Test-tasks

Error was calculated between the produced force and the asked force (mean deviation) for the four virtual tests and the object test (amount of compression). Five separate repeated measures ANOVAs were executed on the error with feedback (LF, TF, and no feedback) and target distance order (20-120, 120-20, and control group) as between-subjects factor and test (pretest, posttest and retention test) as within-subjects factor for all test-tasks and condition as within-subjects factor for four of the five test-tasks. The matching task had no different conditions; the tracking task had three conditions (sine wave, blocked pattern, and compound sine wave); the picture task had six conditions (no compression MO, MO half compressed, MO totally compressed; and no compression HO, HO half compressed, HO totally compressed); and the percentage task had three conditions (25%, 50%, and 75%). After examining the data, the two no-compression conditions of the picture task were removed from the analysis because results on these conditions were not accurate as the applied force was sometimes not measured by the force transducer. Although the instruction was to produce the amount of force needed to lift the object without compression, some of the participants only applied less force than was minimal required to register the force with the force transducer. Therefore the results were too variable to analyze. Moreover, for the object test, only data from 16 participants were analyzed (only the LF 120-20 and the TF 120-20 groups), because the data of the other participants was not collected correctly.

All analyses used a significant criterion of $\alpha = .01$ because of the large number of tests performed, and post hoc tests on main effects used Bonferroni adjustment. In case of violation of sphericity in Mauchly's test the degrees of freedom were adjusted with the Greenhouse-Geisser correction.

Results

Virtual training

An overall decrease of error (Figure 5.3) was seen with practice over the number of targets and over the blocks within each target (Table 5.2). The largest decrease occurred at the beginning of the training period and at the start of each new target, especially in the first two targets presented (small interaction effect of target number by block $F_{(4.99,\ 139.66)} = 5.45$; $p = .00$; $\eta^2_G = .04$). No main effect of feedback was found.

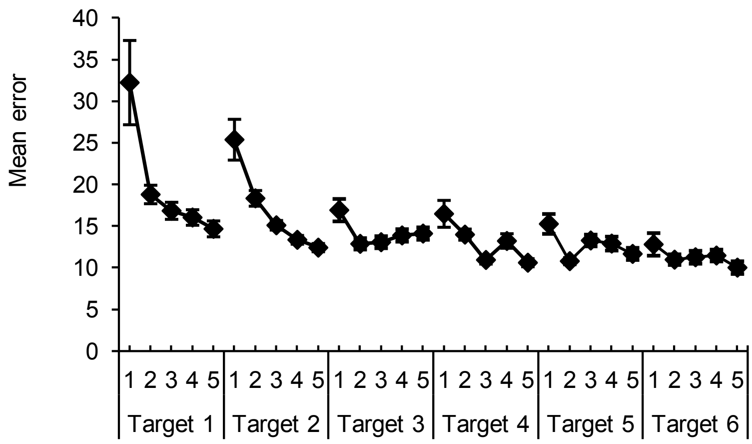


Figure 5.2 *Mean error (SE) across participants over the number of targets that were presented to the participants and the five blocks of 15 trials within each target.*

A large interaction effect of target number by target distance order ($F_{(1.87,\ 52.45)} = 69.03$; $p = .00$; $\eta^2_G = .38$; Figure 5.4A) showed that the distance of the target influenced the amount of error, with a larger distance resulting in more error. Therefore, the two groups that practiced the targets in reverse order differed largely. When comparing the error for each of the target distances (Figure 5.4B), it can be seen that the most relative error is made in the target distance that was started with. The last target distance that was practiced had relatively the least error.

Table 5.1 Statistics of main effects with means and standard errors (SE) in the virtual training for the overall Error during training and the three components Tolerance, Noise, and Covariation

Dependent variable	Factor		Mean (SE)	F	df	*p*	η^2_G
Error	Target	1	19.93 (1.81)	12.80	1.87, 52.45	.00	.07
		2	16.91 (1.52)				
		3	14.16 (1.90)				
		4	13.03 (.72)				
		5	12.77 (.69)				
		6	11.30 (.60)				
	Block	1	19.84 (1.45)	31.34	2.14, 59.78	.00	.05
		2	14.28 (.72)				
		3	13.40 (.68)				
		4	13.47 (.84)				
		5	12.42 (.70)				
Tolerance cost	Target	1	4.76 (.25)	6.93	2.50, 42.49	.00	.06
		2	5.03 (.23)				
		3	5.08 (.22)				
		4	5.53 (.26)				
		5	5.52 (.20)				
		6	5.71 (.26)				
Noise cost	Target	1	11.18 (1.09)	6.35	2.39,66.68	.00	.02
		2	10.04 (.69)				
		3	9.04 (.64)				
		4	8.25 (.60)				
		5	8.09 (.55)				
		6	7.80 (.52)				
	Block	1	10.98 (.74)	8.91	2.94, 82.56	.00	.02
		2	8.91 (.64)				
		3	9.03 (.60)				
		4	8.38 (.62)				
		5	8.03 (.53)				
Covariation cost	Block	1	3.59 (.67)	9.47	2.58,72.28	.00	.02
		2	2.62 (.58)				
		3	2.32 (.55)				
		4	2.34 (.56)				
		5	2.08 (.42)				

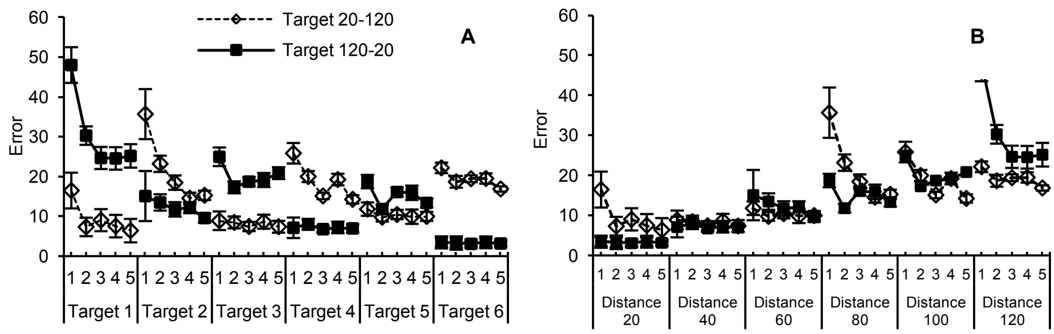
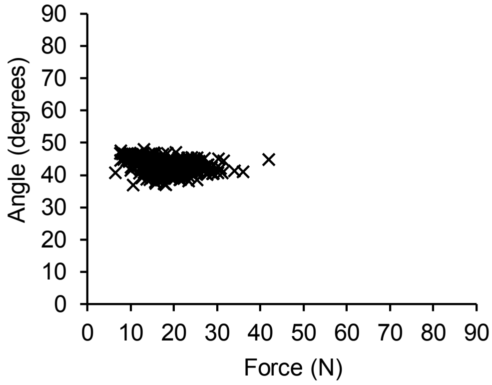


Figure 5.3 *Performance error (SE) of the participants in the target order of performance for each of the five blocks of 15 trials in the practiced number of targets (target 1 to target 6) for both groups that practiced in the order 20-80-40-100-60-120 and 120-60-100-40-80-20 (4A), and the error plotted against each of the target distances (4B) for each of the five blocks of 15 trials within each target distance.*



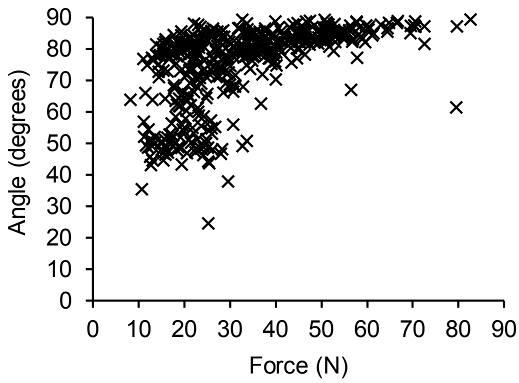


Figure 5.4 *Two typical examples of the strategies seen. One strategy was to hold the angle constant while varying the force (A), the other strategy was to vary both angle and force (B). For each of the strategies, all trials of a typical participant were plotted over sessions and over targets.*

Use of the execution variables force and angle

The median of the applied force was 19.35 N (IQR = 3.42 N), although the range of applied forces was large, ranging from 4 N to 90 N. The median angle used was 49.62 degrees (IQR = 16.36 degrees), with a range from 15 to 88 degrees. Two different strategies were noticed during the training and while examining the data. One strategy was to hold the angle constant while varying the force (12 participants with LF and 6 participants with TF); the other strategy was to vary both angle and force (4 participants with LF and 10 participants with TF; see Figure 5.5 for typical examples). An example of the performance over time in solution space plots is shown in Figure 5.6, in which a typical performance is shown of the 75 trials of a target provided in session 4 and 5. Notice the decrease of variability over trials within session 4, while the spread in error is larger again when the next trials of that target are practiced in a subsequent session. This might be due to temporary increased exploration for the good solution.

Variability measures

T-Cost increased slightly over the number of targets performed (see Table 5.2 for all main effects). The T-cost was not affected by location of the target, nor did the type of feedback result in significant differences. *N-cost* was higher for larger target distances, but decreased overall (Table 5.2). Within most of the targets the noise decreased as well (Figure 5.7). A large target number by target distance order interaction ($F_{(2.39,\ 66.86)}= 89.77$, $p = .00$; $\eta^2_G = .36$) showed that, similar to the overall error, the error was different for the different target distances, and as the 20-120 and the 120-20 groups practiced targets in reverse order, this resulted in a large difference in noise. Type of feedback did not affect N-cost. A small main effect of block revealed that *C-cost* decreased over blocks within each target (Table 5.2), and a trend in decrease of C-cost was seen over the number of targets (p=.05,

η^2_G = .03). A small interaction effect of target number by block ($F_{(5.77, 161.45)}$= 3.92, p = .00; η^2_G = .02) revealed that the C-cost decreased mainly from block 1 to block 2 within the first two targets. A small target number by target distance order interaction ($F_{(1.75, 57.69)}$= 6.10, p = .01; η^2_G = .02) showed that the C-cost differed for the 120-20 and the 20-120 groups over targets, just as the noise and the overall error.

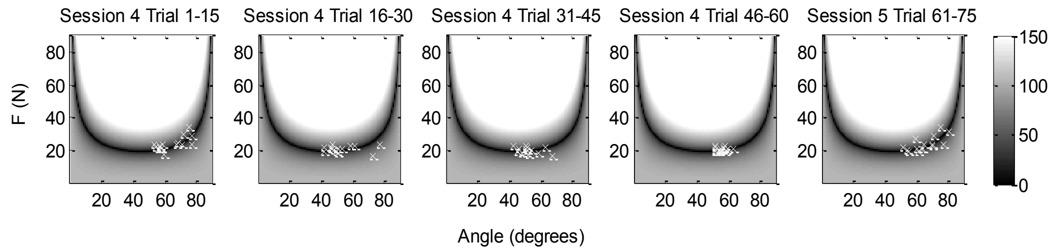


Figure 5.5 *Forces and angles produced by one of the participants from the TF 120-20 group are plotted against each other for all trials of the target with distance 80. Each panel represents 15 trials. During practicing a decrease in variation of data points can be seen over the first four plots, which shows improvement during practice within the target. From session 4 to session 5 a deterioration in performance can be seen, possibly due to increased exploration of the solution space. The shades of grey represent the distance of the ball with regard to the target.*

Box and Blocks training

Participants in the CO group improved their performance time over the sessions from a mean score of 134 seconds to 69 seconds. In the first training sessions, time of performance decreased quickly, while later on the improvement slowed down (Figure 5.8).

Test-tasks

Matching test-task

Main effect of test showed that participants improved in the posttest compared to the pretest, however, their improvement did not last in the retention test (Table 5.3). A small to moderate test by target distance order interaction ($F_{(2, 84)}$= 13.23, p = .00; η^2_G = .09) showed that the deterioration from the posttest to the retention test was mainly due to the 20-120 group; (mean (SE) for 20-120: pretest: 12.34 (1.49); posttest: 11.48 (1.44); retention test: 18.84 (1.28); mean (SE) for 120-20: pretest: 16.89 (1.48) ; posttest: 12.00 (1.44); retention test: 12.85 (1.27); mean (SE) for CO: pretest: 13.85 (1.54); posttest: 11.64 (1.48); retention test: 11.85 (1.32)).

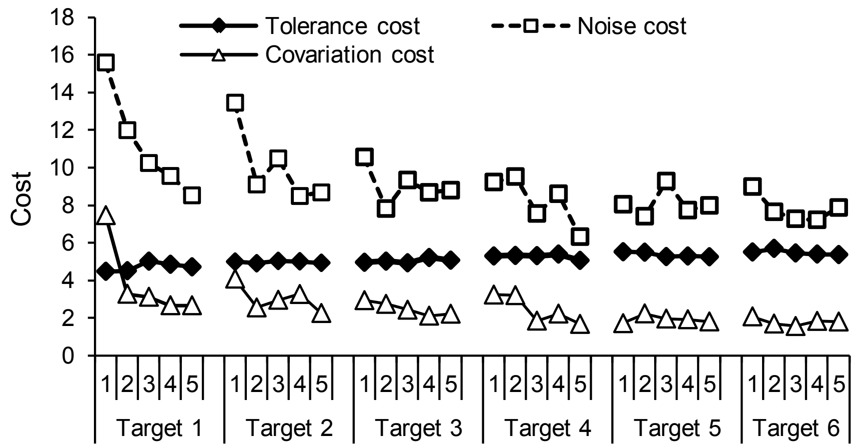


Figure 5.6 *The progress of T-cost, N-cost, and C-cost over the number of targets practiced and over the blocks of 15 trials within the targets.*

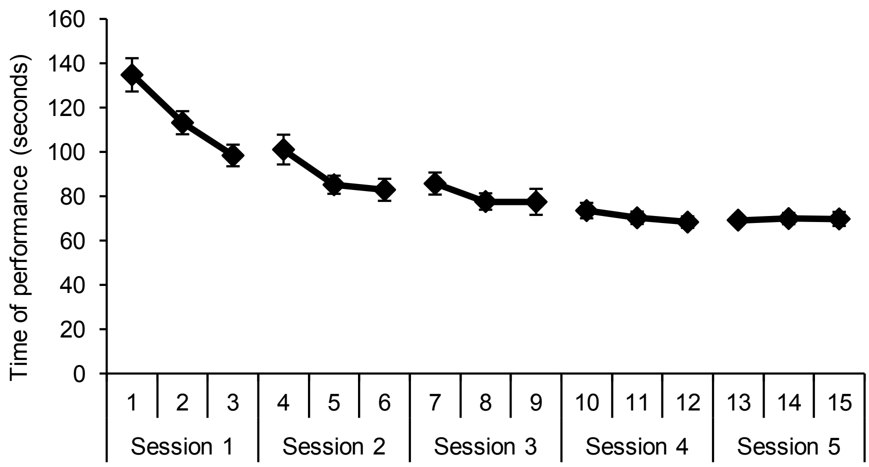


Figure 5.7 *Mean (SE) for the performance on the Box and Blocks training in which 30 blocks had to be transferred from one side of the box to the other.*

Tracking test-task

Participants improved from pretest to posttest in the tracking test-task, and performed on the same level in the retention test (Table 5.3). Figure 5.9 shows typical examples of performance in the pretest and the retention test for the sine pattern and the blocked pattern. The compound sine pattern was executed with the least amount of error, while the greatest error was made on the simple sine pattern, shown in a small main effect of condition. A small main effect of target distance order showed that the CO group and the 120-20 group had significantly less error than the 20-120, revealed with pairwise comparison.

Table 5.2 Main effects in the test-tasks with means and standard errors (SE)

Dependent variable	Factor		Mean (SE)	F	Df	*p*	η^2_G
Matching test	Test	Pretest	14.46 (.90)	7.30	2,84	.00	.05
		Posttest	11.72 (.87)				
		Retention test	15.04 (.77)				
Picture test	Condition	MO half	49.05 (2.95)	37.50	2.05, 86.02	.00	.20
		MO total	41.90 (1.80)				
		HO half	23.16 (1.01)				
		HO total	49.23 (1.47)				
	Target distance order	20-120	44.03 (1.38)				
		120-20	36.11 (1.42)	16.02	1,42	.00	.02
		Control	43.90 (1.38)				
Tracking test	Test	Pretest	11.24 (.69)				
		Posttest	8.61 (.38)	20.35	1.55, 66.61	.00	.09
		Retention test	8.87 (.25)				
	Condition	Sine	10.36 (.44)				
		Blocked	9.54 (.37)	15.59	1.75, 75.25	.00	.02
		Complex Sine	8.83 (.41)				
Percentage test	Condition	25%	30.95 (2.40)				
		50%	31.60 (1.26)	40.49	1.75, 71.63	.00	.21
		75%	19.89 (.85)				
Object test	Test	Pretest	9.66 (.83)	4.62	2, 56	.01	.03
		Posttest	8.30 (.88)				
		Retention test	7.15 (.83)				
	Condition	LO	13.75 (1.02)				
		MO	11.27 (.99)	174.60	1.56, 43.54	.00	.51
		HO	.10 (.06)				

LO: Low-resistance Object; MO: Moderate-resistance Object; HO: High-resistance Object

Percentage test-task

A moderate main effect of conditions was found; the 75% differed significantly from the 25% and 50% of maximal force conditions, shown by pairwise comparison (both p = .00). Participants were more capable to estimate 75% of their maximum force than 25% and 50%. No other effects reached significance.

Object test-task

A main effect of test showed that performance improved from pretest to posttest and retention test, with a significant difference shown between pretest and retention test, indicated by pairwise comparison (Table 5.3). The amount of compression differed largely per object; the object with the highest resistance (HO) was almost not compressed while the most compression occurred in the object with the least resistance (LO) (Table 5.3). A condition by target distance order interaction ($F_{(1.55, 43.54)}$= 6.13, p = .01; η^2_G = .04) revealed that the participants that trained with the 120-20 order compressed the LO and MO objects less than the controls (mean (SE) 120-20: LO: 12.18 (.91); MO: 8.50 (.89); HO: .14 (.05); mean (SE) CO: LO: 15.32 (1.82); MO: 14.03 (1.77); HO: .06 (.11)).

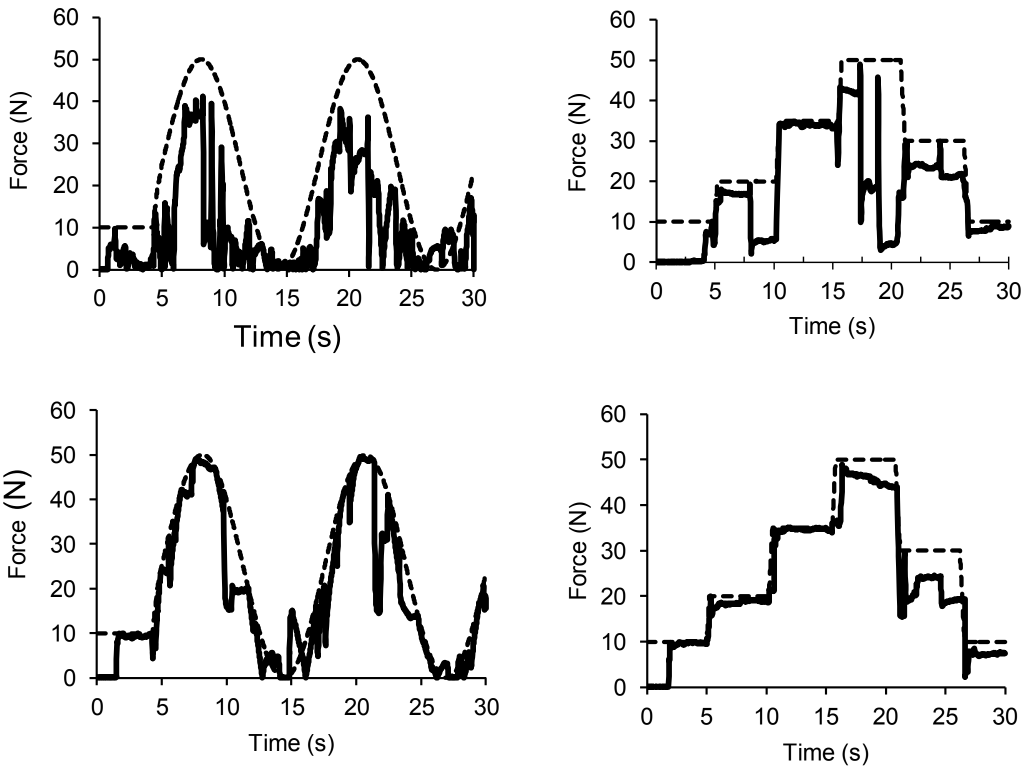


Figure 5.8 *Performance of an arbitrary selected participant of the simple sine pattern and the blocked pattern during the pretest (above) and the retention test (below). The dashed line represents the pattern asked by the computer, the performance of the participant is shown with the thick line. Increasing the applied grip force was easier to control than letting go, shown by larger drops in the signal. This performance was seen in many participants.*

Discussion

Performance during the virtual force control training

The participants decreased their error over the five sessions and within each of the presented targets, which confirms the first hypothesis that was stated in the introduction. This showed that the participants improved their performance over the training sessions and thus, that they were able to learn to improve their control with the help of the virtual training and the visual feedback. The type of feedback did not influence the improvement during training, nor did the order in which the targets were presented. Relatively the most error was made on the first target that was presented and the least amount of error on the last target in the fifth session. The higher error scores for larger target distances was inherent to the design of the task. A shift of 1 degree in the slingshot angle resulted in a small change in the ball's landing position when shooting at a nearby target while in case of a target further away a small change in the angle substantially could affect the landing position.

Analysis of variability over learning

To test the second hypothesis, variability in performance was decomposed into the three components T-cost, N-cost, and C-cost, according to the TNC approach.[111,113] This enabled us to examine what elements contributed the most to the reduction of the error. T-cost did not show large changes during the training period, and therefore did not contribute to improvement. This could be due to the location of the targets used during training. The position of the targets only varied in horizontal direction, which made the solution space of all targets rather alike. It could therefore be that participants found a stable region in the first target and were not challenged to exploit the solution space when new targets had to be reached.[113] The N-cost contributed the most to error in performance, because N-cost was mainly reduced over the training sessions. This finding is in line with the results reported by Cohen and Sternad.[111] When a new target was presented the N-cost increased after which it reduced quickly again over trials. It is likely that participants sought new good solutions by finding new combinations of angle and force.[113] This increased the noise component of variability and, furthermore, the C-cost at the start of a new target, which is what we found.

C-cost was rather small and decreased quickly within each target, as participants anticipated quickly on a change in target location. When a target appeared that was farther away than the previous target, they immediately elongated the slingshot by applying more force to the handle compared to the previous target, and vice versa. This showed that participants anticipated to changes in the demands of the task, and were able to use covariation of the two execution variables to find new successful solutions. The majority of the participants were more inclined to vary the force than the angle when targets changed. They chose mainly angles in the midrange, with the handle pointing upwards, thus, avoiding angles in which they had to position their prosthesis in an awkward posture. In conclusion, to confirm the second hypothesis, the variability in performance decreased over practice, mainly due to a reduction in N-cost.

Influence of feedback on performance

No main effect of feedback was seen during training, although the type of feedback seemed to influence the strategy used. Feedback about the trajectory elicited more combinations of different angles and forces, while feedback about the landing position tended to restrain the variations in the angle in order to find a good solution by only varying the force component. The different strategies were not reflected in the C-cost component of the TNC analysis though, which might indicate that both types of feedback were equally effective to manage the covariation of the two variables and to perform equally during training. Because both strategies ensured the continuous practice of the force component, it can be assumed that the virtual training with visual feedback that is used in this study is suitable for practicing the grip force control.

Unlike in the training, the type of feedback provided during training did seem to influence the transfer of the learned grip force control to the tests. Although the effect of feedback did not reach the significance level of $p = .01$, trends were seen in the data. The near significant effects of feedback on the matching test-task ($p = .04$), tracking test-task ($p = .03$), and the object test-task ($p = .08$), and the near significant interaction of feedback by test in the matching test-task ($p = .02$) and the picture test task ($p = .02$) showed that the feedback on movement execution (TF) was detrimental for the transfer of the learned skill. The TF group improved less from pretest to posttest and scored overall poorer on the retention tests than the landing feedback (LF) group and the control (CO) group.

An explanation for the poorer performance of the TF group could be found in the amount of information provided to the learners during training. Whereas the LF group only received information on the end position of the ball, the TF group received all the information that was available, including the applied force and angle represented by the slingshot and the ball trajectory. According to the guidance hypothesis[141,142,149,150] provision of too much information is detrimental to learning as learners become reliant on the provision of feedback. This does not challenge people to find solutions on their own, while learners are encouraged to actively search for solutions to the problem when less information is available.[151] Moreover, motor planning is believed to be executed in terms of end-effector space.[142] Therefore, actions may be more effective if they are planned in terms of their outcome rather than in terms of the specific movement patterns.

It might be that the LF group learned to actively plan their movements in terms of their outcome, as well as the CO group who achieved similar performances. They could have developed successful solutions based on other information that they found useful during learning. A small part of the proprioceptive information is still present in prosthesis use, which informs about the degree of contraction of the muscle. As the degree of muscle contraction was coupled to the velocity of opening and closing of a prosthetic hand, they might have been able to match the degree of contraction to the result of performance. The participants in the LF virtual group received visual information regarding the end result, whereas the CO group could have learned the scaling of muscle contraction too as they were challenged in an accuracy-velocity trade off to perform as quickly as possible. The TF group, however, might have been unable to pick up this little part of information as it was overruled by the provision of too much visual information.[152] Thus, results in this study show that practicing with more feedback might not always be beneficial to skill learning with a prosthesis, which supports the third hypothesis. It might therefore be better to provide information on the outcome of the movement only.

Improvement in grip force control

To test the fourth hypothesis, grip force control was assessed with five test-tasks that concerned different aspects of the control. In the matching and the tracking test-tasks, which are often used when assessing grip force[134,153-155] performance improved from pretest to posttest. Performance on the two estimation test-tasks, the percentage and the picture test-task, was highly variable between and within participants, and did not show improvement after training. Earlier studies have shown too that performance with a prosthesis is more consistent and less variable with visual feedback than without the provision of information.[103,104] The performance on the task that assessed grip force with real objects instead of virtually, did improve from pretest to retention test. This is an important result because it shows that transfer of learning can occur from this virtual training to a real life task.

The improvements that were seen in performance after training were not very large, while in one test the improvement did not last as performance decreased again in the retention test. It could be that the training was too short to achieve major improvements and consolidation. In an earlier study it has already been shown that improvement in grip force control requires a lot of time.[118] This study supports the statement made in that study; grip force control needs to be practiced over a long period.

Transfer of the learned grip force occurred in the test-tasks that provided instant feedback about performance, while no transfer was seen in the test-tasks that required estimation of the applied grip forces. According to the specificity of practice hypothesis[156], transfer of learning is most effective when the test resembles the training as closely as possible.[140] It is believed that motor learning and skill enhancement improve the most when similar sources of information are available during training and testing.[157] This could explain why transfer did not occur in the estimation tests. The information provided during training and the matching and tracking test-tasks was rather similar as the learners received concurrent feedback on the applied force, either with a change in the elongation of the slingshot or with a change in the signal that represented the applied force in the test-tasks. In the object test-task the participants were able to notice the compression of the object, which provided them with information as well. The estimation tests, on the other hand, did not provide any information about the performance and did not have any similarities with the training. It might therefore be that because the participants did not practice to estimate their applied force without feedback, transfer to the estimation tasks did not occur. Thus, to enhance grip force control learning the most, it might be that training should include the practice of estimating the applied force as well, besides training with feedback on grip force to cover all aspects of grip force control.

Another factor that influenced the transfer of learning was the order of target presentation during training. The participants who practiced in the target distance order 20-120 performed poorer on the tests than the participants who trained with the 120-20 order. The difference between the two target distance orders is that the 20-120 group started with the 20 target which required low forces to be produced in the beginning, whereas the 120-20 group started with the 120 target that allowed for larger forces. As it is more difficult to produce low forces, especially when starting to learn force control[70,117,118], we might therefore conclude that starting with a target in which more force is allowed leads to better performance after training than starting with a difficult target.

Training in virtual reality

The results showed that the virtual training of the LF group was as effective as the functional training, executed by the controls, while the TF group performed poorer after training. Thus, although virtual training seems like a useful method in the rehabilitation process[158], this study shows that one should carefully design a virtual training in order to achieve improved performance and transfer of the learned skills to other tasks than trained. The task that needs to be practiced, the amount and the type of information that is provided, and the difficulty of the training are all aspects that seem to influence the learning process in virtual training.

This study only addressed grip force control in an isolated laboratory setting. What remains to be proven is the transfer of skills when using the prosthesis in everyday life. Is it possible to generalize the skills learned during virtual reality to daily practice? While some studies have already shown that control of the myoelectric signals can be learned virtually (see Dawson et al.[159] for a review), the effectiveness of the virtual training to improve handling the prosthesis in surrounding space and during manipulation of objects needs to be studied in large randomized controlled studies.[159,160] Questions are raised whether the transfer of skill can be made from the virtual environment to the real world, since the visual space (i.e., the screen) is not aligned with the workspace of the movements (i.e., the end-effector such as the hand).[161,162] Sensorimotor transformations need to be learned to map the movements displayed virtually with the movements made with the end-effector.[161,162] The kind of information and the amount of information that is perceived during virtual training plays a role in this issue. In the object test-task, which mimicked an everyday activity the most, improvements were seen for the virtual training group. This could provide indications that it is possible to transfer the skill learned during virtual training to more functional tasks.

Limits of the study

A limitation of the study is the design of the virtual task used in this study. Shooting at larger target distances automatically resulted in higher errors. In order to get a clearer picture on the amount of error made in each target, the task should be designed differently. Moreover, the locations of the targets did not vary in y-position, which resulted in rather similar solution spaces. A future study should include variation in y-position as well in order to challenge the participants to exploit the solution space more. Another limitation of this study is the use of a prosthetic simulator instead of real amputees. Because of the limited number of novice prosthesis users, we chose to study the grip force learning processes with a prosthetic simulator that allowed for inclusion of more participants. An earlier study with the use of the prosthetic simulator provides indications that the use of the simulator might be justified.[118] Comparable scores of a functional test and comparable movement characteristics were shown.

Conclusions

Performance increased during virtual training of force control with a prosthetic simulator, reflected in a reduction in error. Using the TNC approach, variability was shown to decrease mainly as a result of the reduction of N-cost and a good covariation between the used force and angle during training. Grip force control improved only in the test-tasks that provided information on the performance. Although the type of feedback did not influence the improvement during training, it did influence the transfer of the learned grip force control; too much feedback was detrimental to learning. Starting the training with a task that required low force production decreased transfer of the learned skill as well. Based on the results of this study, hints can be provided that might be taken into account when designing evidence-based training programs for prosthesis users. It is recommended to start practicing with easy tasks that allow for high force productions. In addition, it is suggested to train grip force control not only with feedback but also to train on estimation of the applied force. Developers of virtual environments should carefully deal with the provision of information, as too much feedback might prevent effective learning. Moreover, the most effective transfer of the learned skill might be achieved when a learner is provided with feedback about the outcome only.

Acknowledgements
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Appendix A

The following formulas were used to determine for the produced angles (alpha) and forces (F) the parabolic trajectory of the ball- given spring constant c and the balls' mass m. The travelled distance was calculated and the distance between target and ball landing (error).

$c = 1.0$ N/m

$m = 0.5$ kg

$g = 9.81$ m/s^2

Kinetic energy:	$Ek = 0.5 * m * v^2 = Ev = 0.5 * F^2 / c$
Initial velocity of the ball:	$v_i = F / \sqrt{(m * c)}$
y-component of the initial velocity:	$y(t) = v_{i\_y} * t - 0.5 * g * t^2$
x-component of the initial velocity:	$x(t) = v_{i\_x} * t$
Ground hit of the object ($y(t) = 0$):	$t\_g = 2 * v_{i\_y} / g$
Distance traveled at moment of ground hit:	$x(t\_g) = v_{i\_x} * t\_g = 2 * v_{i\_y} * v_{i\_x} / g$
	$v_{i\_y} = v_i * \sin(alpha)$
	$v_{i\_x} = v_i * \cos(alpha)$
	$x(t\_g) = vi^2 * \sin(2 * alpha) / g$
Ball trajectory (conversion from degrees to radians):	$X\_g = vi^2 * \sin(pi * alpha / 90) / g$
Distance between target and ball landing (error):	Error = zeros (size*X_g)) + (X_g < tgt_range(1)) * (tgt_range(1) – X_g) + (X_g > tgt_range(2)) * (X_g – tgt_range(2))

6

Determining skill level in myoelectric prosthesis use with multiple outcome measures

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Abstract

To obtain more insight in how skill level of an upper limb myoelectric prosthesis user is composed, the current study aimed to a) portray prosthetic handling at different levels of description, b) to relate results of the clinical level to kinematic measures, and c) to identify specific parameters in these measures that characterize the level of skill of a prosthesis user. Six experienced transradial myoelectric prosthesis users performed a clinical test (Southampton Hand Assessment Procedure, SHAP) and two grasping tasks. Kinematic measures were end-point kinematics, joint angles, grasp force control, and gaze behaviour. The results of the clinical and kinematic measures were in broad agreement with each other. Participants who scored higher on SHAP showed overall better performance in the kinematic measures. They had smaller movement times, better grip force control, and needed less visual attention to the hand. The results showed that time was a key parameter in prosthesis use, and should be one of the main aspects to focus on in rehabilitation. The insights from this study are useful in rehabilitation practice, because it allows therapists to specifically focus on certain parameters which may result in a higher level of skill for that prosthesis user.

Introduction

Clinical tests are often used in clinical practice to describe upper limb prosthetic function (see Wright[17] for an overview). Such tests of specific tasks serve to assess performance, which aims to provide a general picture of the level of skill of a prosthesis user. For example, the Trinity Amputation and Prosthesis Experience Scales (TAPES)[163] assesses satisfaction with the prosthesis and the influence of the prosthesis on performing activities in daily life. However, the clinical level of description does not supply insight in the processes from which the level of skills originates. That is, the quality of movement execution and why the users perform in that manner, which is important information for rehabilitation practice. More insight into the skill level can be obtained when the score of a clinical test is related to a more kinematic level of description, which can provide detailed information on the actual movement execution assessed by instruments like TAPES. Moreover, by combining multiple levels of description, specific parameters in these movements may be identified that underlie skill level. This might be useful in rehabilitation, because it allows therapists to specifically focus on the parameters on which an individual scores poorly, thereby enhancing the overall level of skill.

To maximize the insight in the factors that contribute to the skill level of a prosthesis user the current study employed a wide range of outcome measures, using a clinical test and several kinematic measures. As such, we follow, and extend, the suggestion put forth in several recent papers that evaluated measures of prosthesis functioning at the clinical level.[17,164,165] In these papers it was concluded that several outcome measures should be combined to provide a complete picture of the functional ability of a prosthesis user, instead of using only one outcome measure. For the clinical test we used the Southampton Hand Assessment Procedure (SHAP)[71] due to its objective character. Although SHAP needs more prosthesis specific validation, this test is a promising, highly relevant measure[17] and considered by the Upper Limb Prosthetic Outcome Measures (ULPOM) group.[166] SHAP is particularly suited for our purposes, since it tests both tasks of daily living as well as tasks with abstract objects, which are the type of tasks mostly used in kinematic measures.

Kinematic measures have been used in several studies to report movement patterns of prosthesis use.[9,22,34,35,41,42,75] These studies measured end point kinematics or joint angles in goal-directed reaching and grasping tasks. Specific characteristics of prosthetic movements and deviations from sound movements were addressed, such as compensatory movements.[34,37] Changes in movement patterns are needed to compensate for the impaired ability of the prosthesis user.[167] However, it is not known which deviations from sound movements are functional, and which movements are excessive. In this study we try to link compensation strategies with the functional abilities, assessed with the clinical test. We assume that participants who scored higher in the clinical test show the most functional compensation strategies. Even with these compensatory movements, we expect that a more skilled prosthesis user will approximate sound movement patterns more closely than a less skilled user.

Furthermore, two aspects that we also assume to define the skill level of a prosthesis user are control of the grip force of the prosthetic hand, and the amount of visual attention needed to operate the prosthesis. It does not appear that these two aspects have ever been studied in prosthesis users previously. However, it is proposed that these two aspects will contribute to the understanding of prosthesis use; therefore we try to fill this gap. Good grip force control is a prerequisite for skilled handling of the prosthesis in daily life, for example, when a prosthesis user holds a drink can or milk carton sufficiently firmly without crushing it in order to open it with their unaffected hand. As the control of grip force is one of the most advanced aspects in the hierarchy of controls training during the rehabilitation period[70], good grip force control requires a high level of dexterity. It is hypothesised that better control of grip force of the hand while grasping non-rigid objects, (i.e., less deformation of the object during grasping), is related to greater skills of the user.

An additional aspect of user control that might reveal the skill level of a user is the amount of visual attention needed to guide the prosthetic hand throughout the execution of a task. One of the aims in rehabilitation (and also in the development of new prostheses) is to decrease the amount of visual feedback that is needed.[65,104] Moreover, the visual attention is one of the main items assessed in the Assessment of Capacity for Myoelectric Control (ACMC).[65] In sound grasping, the eyes usually fixate the object before the hand starts to move, and stay focused on the object while executing the task, whereas the eyes are hardly ever fixated on the hands.[168] In learning to use a prosthesis, the user must visually monitor the hand because the prosthesis does not provide proprioceptive feedback about its aperture. It is expected that better prosthesis skills will be accompanied by less visual support of the prosthesis and that gaze behaviour is more focused on the object, as is the case in sound grasping.

To test our hypotheses, we assessed experienced prosthesis users during a clinical test (SHAP) and by applying two goal-directed fundamental tasks, a direct grasping task with the prosthesis and an indirect grasping task where the object is passed to the prosthesis with the sound hand. In the fundamental tasks, we measured end-point kinematics, joint angles, grip force control, and gaze behaviour. Together with SHAP, these measurements should provide a complete picture of prosthetic control and performance to meet the following objectives: 1) to portray prosthetic handling at different levels of description; 2) to relate the clinical results to the kinematic measures; 3) to identify specific parameters in these measures that characterize the factors contributing to the level of skill of a user.

Methods

Participants

Six experienced users of a myoelectric transradial prosthesis (mean age 36 years; range 19-59; SD 18 years; see Table 6.1 for further characteristics) participated in the study. All participants (P1-P6) used a passive wrist rotator; P4 had also a flexion wrist. The participants all reported a good wearing comfort, except for P2 who experienced the myoelectric prosthesis as heavy, and therefore used a cosmetic prosthesis most of the time. The study was approved by the institutional Research Ethics Board of the University of New Brunswick, Fredericton, Canada (REB 2010-099), and an informed consent was signed by each participant before the start of the experiment.

Apparatus

SHAP consists of 26 tasks: 12 abstract object tasks; six lightweight and six heavyweight objects, and 14 activities of daily living (ADL) to evaluate the functionality of the hand. Time scores of each task provide an overall Index of Functionality score (IoF, a score of the hand function; a sound hand scores normally between 95 and 100, lower scores reflect decreased hand function), and a SHAP Functionality Profile with six prehensile pattern scores.

A Vicon motion analysis system (Vicon, Oxford, sampling frequency 60 Hz) with eight cameras was used to record the positions of 15 reflective markers attached to the participants' head, trunk, and the prosthetic arm in accordance with the upper limb element of the Vicon 'Plug-in-Gait' model (Oxford Metrics, Oxford, England). Furthermore, one marker was attached on the thumbnail and one on the nail of the index finger of the prosthetic hand, and two markers were attached on both sides of each of the objects used in the grasping tasks.

Table 6.1 Characteristics of the participants

Participant	Age (y)	Gender	Cause of amputation	Prosthesis side	Dominancy	Years of prosthesis use	Years of use current myo-electric prosthesis	Frequency of use of myo-electric prosthesis	Activities	Type of myo-electric prosthesis
P1	22	M	Car accident (2008)	Right	Right	2	2	All day, 7 days a week	Everything	Otto Bock DMC, proportional 2 site control
P2	20	F	Congenital	Left	Right	19	5	1 day per week for a couple of hours; other days cosmetic	Only for wheeling	Otto Bock DMC proportional 2 site control
P3	19	F	Congenital	Right	Left	18	5	All day, 7 days a week	Everything	Otto Bock DMC proportional 2 site control
P4	59	M	Industrial accident (2007)	Right	Right	2.5	2.5	3 days per week all day; other days body-powered	Everything	Motion control, 2-site proportional control
P5	44	F	Illness (1992)	Left	Right	17	7	All day, 7 days a week	Everything	Otto Bock digital single site control
P6	54	M	Accident (2005)	Right	Left	4	1	All week, except during working hours (then use of body-powered prosthesis; works 4	Use like cosmetic prosthesis, occasionally opening and	Otto Bock digital single site control

A head-mounted eye tracking system (IScan RK-826 PCI, Inc, MA, USA), synchronized with Vicon, was used to track the gaze behaviour of the participants' left eye with a sample rate of 60 Hz.

Four objects were used in the grasping tasks, three compressible objects and one solid object (all objects were 6 cm x 3.5 cm x 9 cm [w x d x h], see Figure 6.1). The compressible objects consisted of 2 plates with a spring in between. Each spring had a different resistance, requiring a different grip force before the object deformed—Low-resistance object (LO; c = .17 N/mm), Moderate-resistance object (MO; c = .57 N/mm), and High-resistance object (HO; c = 5.31 N/mm). The compressible objects simulated objects used in daily life, like a can or a juice carton. On top of the objects a Velcro cover was mounted. Participants were asked to pull the Velcro off from front to back of the object. This was the manipulation part of the task for each object.

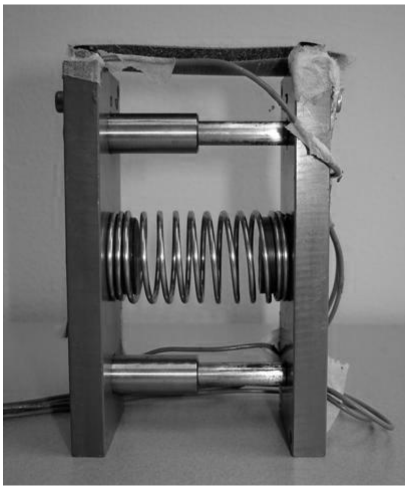

Figure 6.1 *Example of a compressible object, consisting of 2 plates separated by a spring with a set resistance which defined how compressible the object was*

Tasks

SHAP*:* SHAP was conducted according to the standardized procedure. Direct grasping task (DGt): the participants picked up an object in front of them with their prosthetic hand, lifted it up, manipulated the object by pulling off the Velcro cover with the sound hand, and placed the object back on approximately the same position on the table. The starting position of the prosthetic hand in the DGt was located 15 cm from the edge of the table, in line with the shoulder. The object was located 30 cm distal from the initial hand position in line with the shoulder. Indirect grasping task (IGt): the object was initially situated in the sound hand. The participants handed over the object from their sound hand to their prosthetic hand, manipulated the object by pulling off the cover with the sound hand, and placed the object back on the table at the position where the prosthetic hand started. The initial positions of the sound hand and the prosthetic hand in the IGt were 25 cm from the edge of the table opposite to each other in the frontal plane, with 30 cm distance between both hands. The middle between the two hands was aligned with the body midline.

Procedure and Design

Participants were seated comfortably at a table, with the table and chair adjusted in height for each individual. In all trials participants commenced with their prosthetic hand closed. Following a 'ready' signal given by the investigator at the start of each trial the participants were free to initiate the movement. Prior to each task of SHAP, the investigator gave instructions how to execute the task. Each task was timed by the participant by pressing a timer button. For the two grasping tasks the participants were instructed to execute each of the tasks as rapidly and as accurately as possible, while trying not to compress the objects. They were informed about the different object resistances. Each of the objects was grasped 5 times in a random order, resulting in a total of 40 grasping trials.

Data analysis

Because of the individual differences between the participants (differences in prosthesis type etc.) the data were analyzed for each participant separately. An IoF score and a Functionality Profile were calculated for SHAP. The time scores of SHAP were also transformed to z-scores, and mean z-scores were calculated for the lightweight abstract tasks, the heavyweight abstract tasks, and the ADL tasks, to compare the performances on the different parts of SHAP with each other and with other measures.

The onset and termination of the dependent variables in the fundamental tasks were determined with the method of Schot et al.[94] (see Table 6.2) that was implemented in custom written Matlab programs. First, position and velocity for the markers of the hand, thumb, finger and objects were computed. The time from reach onset until reach termination was the reach time; peak velocity was also determined. The grasp was defined by the 3D distance between the markers on the thumb and index finger, and maximum hand aperture was determined. The time between grasp onset and grasp termination defined grasp time. The period from the end of hand opening and the start of hand closure was defined as the plateau phase. Termination synchrony, which reflects the timing of the end of the reach and the grasp, was computed by dividing the time of grasp termination by the time of reach termination. A score of 1 stands for a simultaneous ending of the reach and grasp. When the grasp ended later than the reach, scores exceeded 1, and when the grasp ended before the end of the reach, the scores were below 1. The larger the score, the later was the end of the grasp compared to the end of the reach. For both tasks the measures were computed relative to the position of the object—note that the object moved in the indirect grasping task. Compression of the object was calculated by computing the 3D distance between the two markers on opposite ends of the object.

Table 6.2 Cut-off thresholds of the variables

Variables	Description	DGt	IGt
Start Reach	X-position of the hand on the table	0 < x-position hand < 150 mm	300 < x-position hand > 400 mm
	The hand is closed at the start	aperture hand < 50 mm	aperture hand < 50 mm
	Velocity of the hand starts to increase	15 < velocity hand < 50 mm/s	15 < velocity hand < 50 mm/s
End Reach	The hand must be near the object	380 < x-position hand < 450 mm	80 < distance hand-object < 130 mm
	Velocity of the hand slows down	0 < velocity hand < 10 mm/s	0 < velocity hand < 30 mm/s
	Position of the object is not changed (only DGt)	z-position object < 90 mm	-
Start Grasp	Aperture of the hand starts to increase	20 < aperture hand < 50 mm	20 < aperture hand < 50 mm
	Velocity hand opening starts to increase	velocity hand opening > 20 mm/s	velocity hand opening > 20 mm/s
End Grasp	Aperture of the hand about size object (+markers)	100 < aperture hand < 120 mm	90 < aperture hand < 120 mm
	Velocity hand closing decreases to 0	0 < velocity hand closing < 15 mm/s	15 < velocity hand closing < 50 mm/s
	Grasp has ended as object starts to move (only DGt)	80 < z-position object < 95 mm	-
	Hand must be near object	380 < x-position hand < 450 mm	80 < distance hand-object < 130 mm
Start Plateau	Aperture is around maximum	120 < aperture hand < 180 mm	120 < aperture hand < 180 mm
	Velocity hand opening decreases to 0	10 < velocity hand opening < 50 mm/s	10 < velocity hand opening < 50 mm/s
	Position object is not changed yet (only DGt)	z-position object < 90 mm	-
End Plateau	Aperture is around maximum	120 < aperture hand < 180 mm	120 < aperture hand < 180 mm
	Velocity hand closing starts to increase	30 < velocity hand closing < 100 mm/s	30 < velocity hand closing < 100 mm/s
	Position object is not changed yet (only DGt)	z-position object < 90 mm	-

DGt: Direct Grasping task; IGt: Indirect Grasping task

Joint angles were calculated with the Plug-in-Gait model of Vicon: thorax flexion-extension, side-bending, and rotation, shoulder flexion-extension, abduction-adduction and rotation, and elbow flexion-extension. Range of Motion (ROM) for each joint was calculated by subtracting the minimum value of the angle from the maximum value in each trial.

To examine the gaze behaviour, the scene video produced by IScan with the Point of Regard (PoR) superimposed was scored frame by frame with Anvil 5.0 video-annotation software (German Research Centre for Artificial Intelligence (DFKI), Saarbrücken, Germany). The image was divided in the following areas: object, hand, object and hand, other, and endpoint for the scoring of the PoR.

Two Kruskall-Wallis tests were executed on the dependent variables, one with grasp type (DGt and IGt) as grouping variable and one with object (LO, MO, HO, and S) as grouping variable, using SPSS 16.0. The Bonferroni correction was used to correct for the multiple comparisons for each of the dependent variables within the two tests, resulting in a significance level of .05/8 = .006.

Spearman's Rho Correlation was calculated between the mean z-score of the time scores of SHAP, each of the endpoint kinematics, and gaze behaviour.

Trials were rejected when markers were obscured so that one or more of the above mentioned variables could not be determined.

Results

General remarks

P1 was loaned a hand to perform the experiment, as his prosthesis was broken at the time of the study. This hand was of the same type as the one the participant normally used, except that it did not have a flexion wrist. For P3 the corneal reflex, needed to track the eye, was not found by the IScan equipment, therefore there are no results on the gaze behaviour of P3. Due to problems with the prosthesis, the control mode of the prosthesis of P5 had to be changed just before the experiment, which resulted in a subjective poorer control of the prosthesis during the experiment since the participant had to get used to the new control system. Moreover, the markers on the fingers of P5 were occluded during the IGt; therefore the endpoint kinematic data of the IGt is not presented for P5. P6 was cognitively challenged, and sometimes had difficulties to follow the instructions.

Because we wanted the participants to reflect the population of prostheses users this participant was not removed.

SHAP

In Table 6.3 the z-scores and the scores of the IoF and the six prehensile patterns are presented. A negative z-score means better performance than the average score of the participants over all tasks, whereas a positive z-score means that the participant performed worse than the average score. The IoF score of all participants was far below the normal score of 95-100, with large differences between the participants. P1 scored the highest, whereas P5 and P6 scored much lower. This is also reflected in the z-scores, as the z-scores of P5 and P6 were mostly positive, whereas the scores of the other participants were mainly negative. Overall, the highest scores were obtained in the spherical grip whereas the participants scored the lowest on the tip grip.

Table 6.3 SHAP mean z-scores, Index of Functionality (IoF) and scores of prehensile patterns

	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Abstract – Lightweight	-.77	-.34	-.50	-.27	.32	.[a]
Abstract – Heavyweight	-.82	-.35	-.37	-.64	.73	1.46
Activities of daily living (ADL)	-.63	-.51	-.25	-.37	.64	.[a]
IoF	71	65	62	57	33	17
Spherical	77	77	80	78	56	23
Tripod	63	49	47	29	28	0
Power	69	61	61	42	39	7
Lateral	77	63	57	77	19	29
Tip	59	33	32	42	12	8
Extension	73	70	79	69	54	17

a. no mean z-score could be calculated because of missing scores; for the abstract-lightweight objects P6 could not execute the tripod task, and for the ADL task P6 was not able to execute the food task, the zipper task, and the screwdriver

Endpoint kinematics and object compression

Figure 6.2 shows a typical profile of the performance of two of the participants during a DGt trial. During the reach of the hand towards the object (Figure 6.2A), the hand opened to a maximum aperture, plateaued, and started to close when the hand was near the object (Figure 6.2B). When the object was picked up, two moments of compression could be determined (Figure 6.2C). The first compression occurred directly at the moment when the object was picked up (indicated with arrow 1), and the second, subsequent compression occurred when the Velcro strip was pulled off (indicated with arrow 2). The difference between the two participants can clearly be noticed in the velocity of the hand during the reach, the time needed to execute the task, the length of the plateau in the aperture, and the amount of compression of the object. In Table 6.4 (A and B) and Table

6.5 (A and B) the significant effects of grasping task and object, respectively, on the dependent variables describing this behaviour are presented.

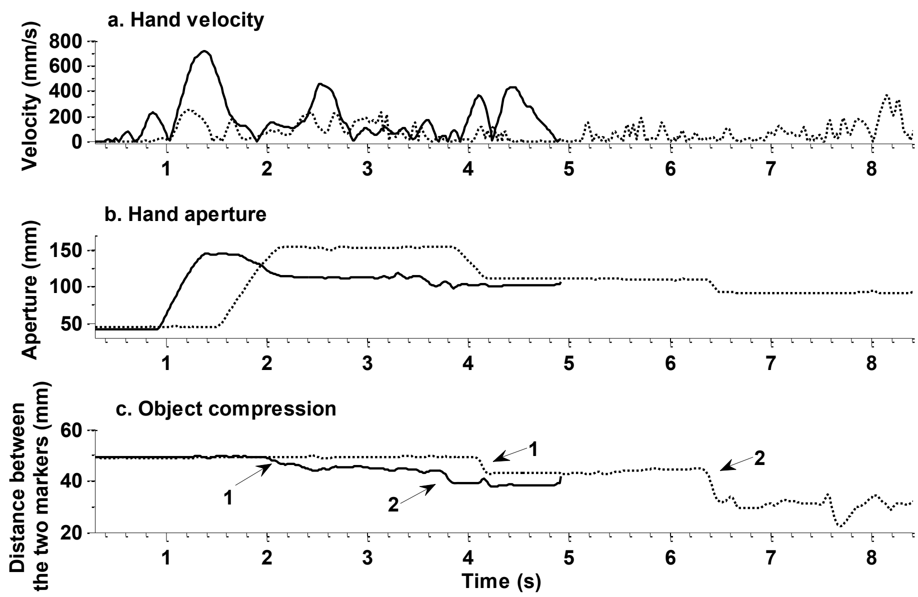

Figure 6.2 *Example of two participants who performed a direct grasp with a compressible object. The solid line represents the participant who scored the highest on SHAP; the dashed line represents the participant who scored the lowest on SHAP.*

The different grasping tasks influenced variables of the movement of the hand towards the object (Table 6.4 A and B), whereas the effect of the objects was mainly reflected in the dependent variables of the grasp and object manipulation (Table 6.5 A and B). The DGt had longer reach times, longer plateau times, longer total grasp times, lower peak velocities, and larger apertures compared to the IGt (Table 6.4 A and B). No significant differences were found in the termination asynchrony and the compression of the object. However, the mean scores of each participant showed that the asynchrony was slightly higher for the IGt compared to the DGt. Moreover, the objects were less compressed during the IGt. P3 had the best performance as she picked up the object with almost no compression at all.

The different object resistances influenced several variables; an object with lower resistance had longer total grasp time, less synchronization of the end of the reach and the grasp, and more compression of the object (Table 6.5 A and B). As expected, effect of object resistance on the amount of compression of the object was significant in all participants. No significant effect was found in the plateau time, however, it can be noticed that the plateau time decreased with an increasing object resistance.

Although no statistical comparisons were executed between the participants, P5 and P6 scored generally lower than the other participants, reflected in longer times, smaller peak velocities, and more compression of the objects.

Table 6.4A Mean, SD, 95% Confidence Interval (CI), and H for the significant effects of grasping on the dependent variables of P1, P2, and P3

Variables		**P1**		**P2**		**P3**	
		DGt	**IGt**	**DGt**	**IGt**	**DGt**	**IGt**
Reach Time (s)	Mean	1.49	1.06	1.46	1.31	1.48	.96
	SD	.25	.26	.23	.48	.25	.19
	95% CI lb	1.39	.96	1.34	.95	1.35	.86
	95% CI ub	1.58	1.16	1.58	1.68	1.61	1.06
	H	24.96		1.22		21.22	
	p	.00*		.27		.00*	
Peak Velocity (mm/s)	Mean	664.39	641.58	337.51	394.95	369.22	724.65
	SD	81.47	202.84	66.76	118.46	61.38	136.90
	95% CI lb	633.40	561.34	301.93	303.90	337.66	656.57
	95% CI ub	895.38	721.82	373.08	486.01	400.78	792.73
	H	.07		1.55		25.17	
	p	.79		.21		.00*	
Plateau Time (s)	Mean	.40	.39	.91	.97	.51	.22
	SD	.23	.37	.37	.43	.29	.14
	95% CI lb	.32	.24	.71	.64	.36	.15
	95% CI ub	.49	.53	1.11	1.30	.66	.29
	H	2.04		.08		10.48	
	p	.15		.78		.00*	
Total Grasp Time (s)	Mean	1.64	1.30	2.37	2.79	2.10	1.43
	SD	.39	.56	.75	.93	.81	.47
	95% CI lb	1.49	1.08	1.98	2.07	1.68	1.20
	95% CI ub	1.79	1.52	2.77	3.50	2.52	1.67
	H	22.18		.87		12.87	
	p	.00*		.35		.00*	
Maximal Aperture (mm)	Mean	144.61	134.17	142.71	134.15	126.82	120.14
	SD	1.51	9.24	5.37	10.64	7.15	6.24
	95% CI lb	144.04	130.52	139.84	125.97	123.14	117.04
	95% CI ub	145.19	137.82	145.57	142.33	130.50	123.25
	H	13.79		3.49		7.50	
	p	.00*		.06		.01	
Termination Asynchrony	Mean	1.20	1.24	1.72	2.12	1.48	1.62
	SD	.11	.21	.32	.50	.42	.47
	95% CI lb	1.16	1.15	1.55	1.74	1.26	1.38
	95% CI ub	1.25	1.32	1.89	2.50	1.70	1.85
	H	.15		3.71		.85	
	p	.70		.05		.36	
Compression during Grasp (mm)	Mean	4.68	1.60	4.08	2.51	.29	.67
	SD	5.65	2.90	4.25	1.34	.33	.76
	95% CI lb	2.53	.45	1.82	1.48	.12	.29
	95% CI ub	6.83	2.75	6.35	3.54	.46	1.05
	H	5.17		.24		1.25	
	p	.02		.63		.26	

df 1 for all dependent variables and participants; * significant at .006 level; alpha of .05 corrected with Bonferroni correction for the 8 tests; DGt: Direct Grasping task; IGt: Indirect Grasping task; lb = lower bound; ub = upper bound

Table 6.4B Mean, SD, 95% Confidence Interval (CI), and H for the significant effects of grasping on the dependent variables of P4, P5, and P6

		P4		**P5**[a]		**P6**	
		DGt	**IGt**	**DGt**	**IGt**	**DGt**	**IGt**
Reach Time (s)	Mean	1.64	1.09	2.27		3.18	2.89
	SD	.34	.95	.95		1.92	1.24
	95% CI lb	1.47	.95	1.91		1.89	2.21
	95% CI ub	1.81	1.24	2.63		4.47	3.58
	H	16.56				.27	
	p	.00*				.60	
Peak Velocity (mm/s)	Mean	477.15	683.54	247.98		268.56	562.22
	SD	134.82	196.69	58.44		73.51	195.63
	95% CI lb	407.83	569.97	225.75		219.17	453.89
	95% CI ub	546.47	797.10	270.21		319.95	670.55
	H	9.10				15.35	
	p	.00*				.00*	
Plateau Time (s)	Mean	.96	.90	1.10		1.57	1.84
	SD	.53	.59	.61		1.39	1.13
	95% CI lb	.69	.56	.86		.63	1.22
	95% CI ub	1.24	1.24	1.33		2.50	2.47
	H	.54				.92	
	p	.46				.34	
Total Grasp Time (s)	Mean	2.22	2.46	2.22		5.21	3.69
	SD	.87	1.01	.68		4.14	1.34
	95% CI lb	1.78	1.88	1.96		2.43	2.94
	95% CI ub	2.67	3.05	2.48		7.99	4.43
	H	.57				.49	
	p	.45				.48	
Maximal Aperture (mm)	Mean	132.68	129.36	150.57		162.81	163.39
	SD	.97	2.02	.74		10.52	10.95
	95% CI lb	132.18	128.19	150.29		155.74	157.33
	95% CI ub	133.17	130.53	150.60		169.87	169.45
	H	15.76				1.13	
	p	.00*				.29	
Termination Asynchrony	Mean	1.33	1.85	1.44		1.61	1.68
	SD	.28	.62	.39		.36	.56
	95% CI lb	1.19	1.50	1.29		1.37	1.37
	95% CI ub	1.47	2.21	1.59		1.85	2.00
	H	7.72				.02	
	p	.01				.90	
Compression during Grasp (mm)	Mean	8.48	2.70	3.89		7.08	6.66
	SD	7.96	3.62	5.47		7.88	7.52
	95% CI lb	4.39	.61	1.81		1.79	2.49
	95% CI ub	12.57	4.79	5.97		12.38	10.82
	H	1.84				.001	
	p	.18				.98	

df 1 for all dependent variables and participants; * significant at .006 level; alpha of .05 corrected with Bonferroni correction for the 8 tests; [a] since there are no outcome measures of the IGt, the Kruskal-Wallis test could not be performed for P5; DGt: Direct Grasping task; IGt: Indirect Grasping task; lb = lower bound; ub = upper bound

Table 6.5A Mean, SD, 95% Confidence Interval (CI), and H for the effects of objects on the dependent variables for P1, P2, and P3

Variables		P1 LO	P1 MO	P1 HO	P1 S	P2 LO	P2 MO	P2 HO	P2 S	P3 LO	P3 MO	P3 HO	P3 S
Plateau time (s)	Mean (SD)	.51 (.37)	.37 (.29)	.38 (.29)	.33 (.23)	1.01 (.40)	1.15 (.46)	.91 (.24)	.70 (.42)	.38 (.14)	.36 (.37)	.36 (.27)	.35 (.24)
	CI lb – ub	.30 – .73	.21 – .53	.19 – .57	.20 –.45	.67 – 1.34	.42 – 1.89	.69 – 1.13	.26 – 1.14	.24 –.53	.07–.65	.16 – .55	.18 – .52
	H	3.53				3.63				.82			
	P	.32				.30				.84			
Total Grasp Time (s)	Mean (SD)	1.96 (.43)	1.36 (.39)	1.36 (.47)	1.25 (.43)	3.09 (.77)	2.81 (1.08)	2.29 (.54)	1.84 (.41)	2.59 (1.19)	1.69 (.39)	1.53 (.57)	1.55 (.45)
	CI lb – ub	1.71 – 2.21	1.14 – 1.57	1.05 – 1.67	1.02 – 1.47	2.44 – 3.73	1.09 – 4.53	1.80 – 2.79	1.42 – 2.27	1.34 – 3.84	1.39 – 1.99	1.12 – 1.93	1.23 – 1.87
	H	16.06				8.19				7.60			
	P	.00*				.04				.06			
Termination Asynchrony	Mean (SD)	1.40 (.21)	1.18 (.07)	1.16 (.10)	1.14 (.08)	2.26 (.48)	1.84 (.33)	1.72 (.22)	1.53 (.14)	2.04 (.54)	1.62 (.43)	1.36 (.37)	1.38 (.26)
	CI lb – ub	1.28 – 1.53	1.13 – 1.22	1.09 – 1.22	1.10 – 1.19	1.86 – 2.66	1.31 – 2.37	1.52 – 1.92	1.38 – 1.67	1.48 – 2.61	1.29 – 1.95	1.10 – 1.62	1.20 – 1.57
	H	13.92				10.98				8.59			
	P	.00*				.01				.04			
Compression during grasp (mm)	Mean (SD)	3.29 (3.63)	8.15 (5.88)	.97 (.69)		6.19 (3.88)	5.55 (3.15)	2.31 (.97)		1.16 (.88)	.66 (.56)	.41 (.36)	
	CI lb – ub	1.19 – 5.39	4.90 – 11.4	.50 – 1.44		2.95 – 9.44	.53 – 10.6	1.41 – 3.21		.23 – 2.08	.23 – 1.09	.16 – .67	
	H	41.44				17.95				23.17			
	P	.00*				.00*				.00*			
Compression during manipulation (mm)	Mean (SD)	12.6 (7.40)	12.6 (4.24)	2.40 (.65)		18.9 (4.04)	15.2 (5.47)	6.89 (2.30)		9.10 (2.38)	5.53 (2.93)	2.18 (1.12)	
	CI lb – ub	8.34 – 16.9	10.2 – 14.9	1.97 – 2.84		15.5 – 18.8	6.51 – 23.9	4.76 – 9.02		6.61 – 11.6	3.28 – 7.78	1.37 – 2.98	
	H	46.88				20.72				29.84			
	P	.00*				.00*				.00*			

df = 3 for all dependent variables and participants; * = significant at .006 level; alpha of .05 corrected with Bonferroni correction for the 8 tests; LO = Low- resistance Object; MO = Moderate-resistance Object; HO = High-resistance Object; S = Solid object; CI lb = 95% confidence interval lower bound; CI ub = 95% confidence interval upper bound; PT = plateau time; TGT = total grasp time; TS = termination synchrony; CG = compression at grasp; CM = compression at manipulation

Table 6.5B Mean, SD, 95% Confidence Interval (CI), and H for the effects of objects on the dependent variables for P4, P5, and P6

Variables		P4				P5				P6			
		LO	MO	HO	S	LO	MO	HO	S	LO	MO	HO	S
Plateau time (s)	Mean (SD)	.84 (.35)	1.10 (.68)	.86 (.74)	.97 (.45)	.98 (.41)	1.34 (1.06)	1.21 (.43)	.86 (.27)	1.81 (.69)	1.76 (1.17)	2.13 (1.50)	1.28 (1.43)
	CI lb – ub	.57 – 1.11	.47 – 1.73	.25 – 1.39	.56 – 1.39	.55 – 1.41	.36 – 2.31	.85 – 1.57	.63 – 1.09	1.17 – 2.45	.11 – 3.62	.74 – 3.51	.09 – 2.47
	H	2.07				4.73				3.8			
	P	.56				.19				.28			
Total Grasp Time (s)	Mean (SD)	2.11 (.55)	2.79 (1.10)	2.48 (1.29)	1.99 (.50)	2.41 (.75)	2.51 (.83)	2.28 (.62)	1.77 (.35)	3.85 (.88)	3.40 (.56)	4.79 (1.96)	4.82 (4.98)
	CI lb – ub	1.69 – 2.53	1.78 – 3.80	1.40 – 3.56	1.53 – 2.46	1.62 – 3.20	1.75 – 3.28	1.76 – 2.80	1.47 – 2.07	3.03 – 4.66	2.50 – 4.29	2.98 – 6.60	.66 – 8.99
	H	1.68				7.79				2.48			
	P	.64				.05				.48			
Termination Asynchrony	Mean (SD)	1.47 (.26)	1.97 (.85)	1.51 (.45)	1.35 (.26)	1.56 (.31)	1.61 (.61)	1.38 (.30)	1.25 (.22)	1.42 (.20)	1.84 (.76)	1.99 (.50)	1.47 (.32)
	CI lb – ub	1.27 – 1.66	1.19 – 2.76	1.14 – 1.89	1.11 – 1.60	1.23 – 1.89	1.04 – 2.18	1.13 – 1.63	1.06 – 1.43	1.24 – 1.61	.63 – 3.06	1.52 – 2.45	1.21 – 1.74
	H	2.49				4.95				8.01			
	P	.48				.18				.05			
Compression during grasp (mm)	Mean (SD)	10.0 (7.80)	8.67 (7.43)	3.88 (4.46)		9.18 (6.08)	7.59 (5.47)	.59 (.30)		14.6 (6.14)	12.2 (6.80)	3.81 (3.42)	
	CI lb – ub	4.03 – 16.0	1.80 – 15.5	.16 – 7.61		2.80 – 15.6	2.53 – 12.6	.34 –.84		8.95 – 20.3	1.34 – 23.0	.64 – 6.97	
	H	18.71				22.76				21.24			
	P	.00*				.00*				.00*			
Compression during manipulation (mm)	Mean (SD)	22.3 (7.54)	28.6 (4.02)	19.0 (7.27)		19.2 (5.83)	21.8 (2.15)	15.5 (6.71)		26.0 (7.67)	21.7 (3.42)	14.4 (5.85)	
	CI lb – ub	16.5 – 28.1	24.9 – 32.3	12.9 – 25.1		13.1 – 25.4	19.9 – 23.8	9.94 – 21.1		18.9 – 33.1	16.2 – 27.1	8.96 – 19.8	
	H	22.11				19.15				21.67			
	P	.00*				.00*				.00*			

df = 3 for all dependent variables and participants; * = sigificant at .006 level; alpha of .05 corrected with Bonferroni correction for the 8 tests; LO = Low- resistance Object; MO = Moderate-resistance Object; HO = High-resistance Object; S = Solid object; CI lb = 95% confidence interval lower bound; CI ub = 95% confidence interval upper bound; PT = plateau time; TGT = total grasp time; TS = termination synchrony; CG = compression at grasp; CM = compression at manipulation

Joint angles

In Table 6.6 the average ROM of the thorax, the shoulder, and the elbow are displayed for each participant. The overall movement pattern of the participants during the DGt was flexion of the trunk combined with some trunk side bending towards the prosthesis side while rotating to the non-prosthesis side with the trunk. In order to pick up the object, the shoulder of the prosthetic arm moved in anteversion and internal rotation and the elbow was extended. There was much variation in the amount of shoulder abduction between the participants. Participant P1 and P4 abducted their arm much more during the trial (an average of 50 and 30 degrees, respectively), while P5 and P6 limited their abduction to only 10 degrees. The starting position of the arm differed largely between the participants, P1 and P3 started with an abduction of 40 degrees, P2 and P4 started at 20 degrees, and P5 and P6 had only about 10 degrees of abduction at the start of the trials (Figure 6.3).

Table 6.6 Mean (SD) Range of Motion for the shoulder, elbow, and thorax angles for the direct grasping task (DGt) and the indirect grasping task (IGt)

Task	P	Shoulder			Elbow	Thorax		
		Flexion-Extension	Abduction-Adduction	Rotation	Flexion-Extension	Flexion-Extension	Side bending	Rotation
DGt	P1	30.17 (5.38)	62.32 (9.16)	36.98 (4.90)	36.61 (7.93)	19.69 (2.55)	16.47 (1.85)	18.69 (1.98)
	P2	32.75 (4.14)	21.33 (3.18)	42.30 (4.84)	32.47 (3.87)	8.83 (1.65)	8.91 (1.97)	14.70 (3.48)
	P3	34.44 (2.65)	17.96 (8.12)	43.31 (31.02)	42.55 (1.45)	5.79 (0.99)	6.20 (1.79)	7.17 (1.13)
	P4	35.31 (3.14)	33.22 (6.47)	32.21 (6.37)	33.61 (2.92)	12.58 (2.19)	7.56 (1.66)	7.84 (0.94)
	P5	47.10 (6.34)	15.83 (3.27)	25.01 (5.71)	31.86 (6.82)	19.15 (1.60)	7.47 (1.56)	12.96 (2.59)
	P6	49.36 (43.56)	39.85 (49.43)	31.29 (5.71)	34.41 (3.34)	16.34 (5.46)	12.56 (6.21)	14.22 (1.70)
IGt	P1	16.14 (4.22)	12.80 (6.00)	23.56 (7.19)	17.71 (3.07)	3.90 (1.89)	4.28 (2.12)	3.03 (1.25)
	P2	13.77 (2.14)	26.38 (3.48)	26.43 (5.33)	12.09 (3.10)	4.29 (1.30)	2.27 (1.03)	5.10 (1.96)
	P3	14.81 (5.22)	21.69 (5.25)	25.94 (4.07)	11.60 (2.24)	3.12 (0.94)	3.26 (1.44)	2.70 (1.06)
	P4	15.01 (34.24)	25.02 (37.22)	21.28 (5.43)	15.68 (3.27)	2.39 (1.01)	3.99 (0.85)	2.05 (0.88)
	P5	8.70 (1.44)	6.78 (1.68)	20.27 (3.64)	5.61 (2.23)	3.39 (0.85)	3.80 (0.97)	4.10 (1.32)
	P6	13.25 (3.73)	12.50 (3.58)	36.39 (3.88)	23.48 (7.32)	9.64 (2.13)	4.40 (1.85)	3.58 (0.87)

P = participant

For the IGt the movement pattern was slightly different, with almost no movement in the trunk (see Table 6.6). The shoulder moved in anteversion and internal rotation during the trial, but less than during the DGt. Again, there was much variation in the amount of shoulder abduction, especially in the starting position of the arm. P1 started with a large shoulder abduction angle, P5 and P6 with almost no abduction, and P2, P3, and P4 with an angle between 20 and 40 degrees (Figure 6.3). There was only a small degree of variation in the elbow angle during task execution for all participants.

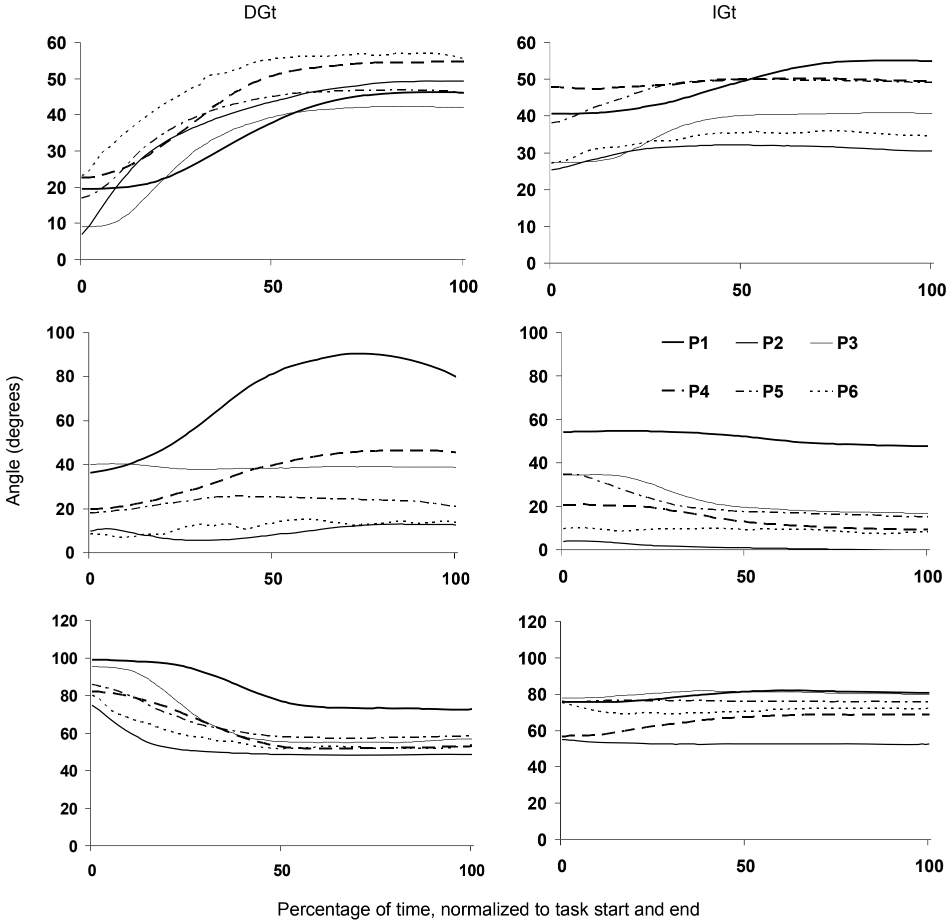

Figure 6.3 *The average joint angle of each participant for the elbow flexion-extension, the shoulder flexion-extension, and the shoulder abduction-adduction, plotted against normalized time for both the direct grasping task and the indirect grasping task.*

Eye movements

Overall, two types of gaze behaviours were found. P1, P4, and P5 first fixated the object after the start of the trial and looked at the object most of the time during the trials. The average gaze behaviour of P2 and P6 was for about two third of the trials, (distributed throughout the whole session) to look quickly at the object at the start of the trial, then at their prosthetic hand followed again by the fixation of the object again. For the other third of the trials, P2 and P6 looked first at the hand before looking at the object, especially during the DGt. During execution of a trial the gaze of P2 and P6 switched repeatedly between the hand and the object. The difference in behaviour can be seen in Figure 6.4 (A and B), the total number of fixations per trial is larger for P2 and P6 than for the other participants (Figure 6.4A), while especially for P2 and a bit less for P6 the percentage of duration of fixation on the object is lower whereas the percentage of duration of fixation in the hand is higher (Figure 6.4B). Note that P2 and P6 are the participants who did not use their myoelectric prosthesis much during the day. No differences in gaze behaviour were found between the four different objects.

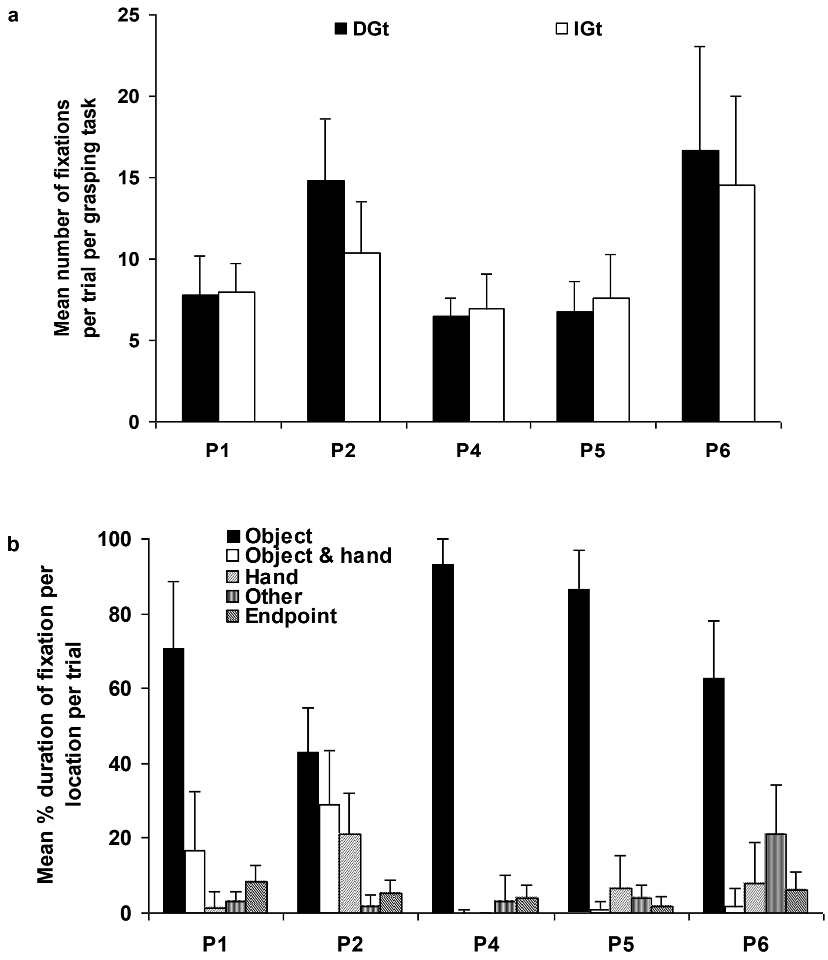

Figure 6.4 *Mean number of eye fixations per trial for each of the grasping tasks (DGt and IGt) (a), and mean percentage of duration of the eye fixations per location in a trial (b) for each of the participants (P1-P6).*

Correlation between SHAP and the motion analysis results

To determine whether the different measures are related, we performed correlation analyses between the measures. Also in these results, the differences in the performance of the participants can be seen, as P5 and P6 (who scored lower in SHAP and had more deviations from sound behaviour in the endpoint kinematics) are positioned at one side of the distribution whereas for example P1 and P3 are located at the other end. The mean z-score of the heavyweight abstract tasks of the SHAP correlated significantly with the reach time of the DGt and IGt (r_s = .83, p = .04); the better the score (i.e., the more negative the z-score), the shorter the reach time. A more negative z-score of the heavyweight abstract tasks was significantly correlated with a higher peak velocity (r_s = -.83, p = .04). Importantly, a shorter plateau time was related to a more negative z-score of the lightweight abstract tasks (r_s = .90, p = .04). Note that the occurrence of the plateau in the grasping profile is a distinguishing characteristic of prosthetic use. There were no other significant correlations.

Discussion

The aims of this study were to portray prosthetic functioning at different levels of description, to relate the results of the clinical outcome measures with the results of the kinematic measures, and to identify specific parameters that characterize the level of skill of a user. We assumed that a more skilled prosthesis user would score higher on SHAP, and that better skills would be reflected in better functional compensation strategies, better grip force control of the hand, and more approximation to sound movement patterns and sound gaze behaviour. Our findings show that, overall, the results confirmed our hypotheses.

Although the scores on SHAP were far below the normal score with a sound hand, the scores provided a good basis for the level of skill of the prosthesis user. The test reflected differences between the functional abilities of the participants as was also found previously.[116] Like in the study of Kyberd et al.[116], our participants scored the lowest on the tip grip, despite the fact that their hand was—by default—set in tip grip. This was only logical, however, since the most difficult tasks were included in the tip grip score, such as picking up coins, the zipping task, and the screwdriver task. The functional ability of each participant scored by SHAP was confirmed by the kinematic measures. As expected, the higher the score on SHAP (thus the closer to a normal score) the more the movement and gaze patterns of the prosthesis user approximated those of sound, able-bodied persons.

The participants who scored higher on SHAP, showed movement patterns in the endpoint kinematics that deviated less from sound movement patterns[75], with shorter movement times, shorter plateau times, and less object compression.

Overall, similar movement profiles were found as reported in earlier studies with prosthesis users[75,41,42], with the characteristic plateau phase bridging hand opening with hand closing. Indirect grasping seemed to be easier to perform than direct grasping, based on the shorter times, the higher peak velocities, the smaller maximum hand apertures (the larger apertures in the DGt were probably to increase the tolerance for errors), and less compression of the objects during that task. These findings are in agreement with the fact that indirect grasping is more often performed with a prosthesis in daily life[89] than direct grasping. Moreover, in the IGt the sound hand contributes to the performance as well, whereas the DGt is executed with the prosthetic hand alone. The large effect of the objects for all participants revealed that they were all able to adjust the grip force to the characteristics of the object; although participants who scored higher on SHAP compressed the objects less intensely or, in other words, they showed a better grip force control.

Overall, the movement patterns in the joint angles were rather similar for all participants, except for the variation in the amount of shoulder abduction. We interpreted that more shoulder abduction was used to compensate for the lack of wrist movement in the prosthesis. Although P4 had a flexion wrist, his movement patterns were not different from the other participants who did not have this additional function. We assumed that the better performing participants would show the most functional compensation strategies, and that movement patterns of higher skilled participants would more resemble sound movement patterns. However, in this regard results were different than expected. P1, who overall performed best out of the six participants, had the largest abduction angles in the shoulder, while P5 and P6, the two participants with the lowest performance, showed the smallest abduction angles. This implies that participants with the highest functional scores may also show movement behaviours that largely deviate from sound behaviour (i.e., extensive compensatory behaviour), which is contrary to what we anticipated. Usually, the aim of rehabilitation is to reduce compensatory movements as much as possible[34,37] and to bring movement patterns back as close as possible to those of sound movement patterns[167], to reduce load and strain to joints as well as to avoid injuries and overuse. However, an alternative view on compensatory movements, put forth by Latash and Anson[167], is that these movements reflect a solution given the motor characteristics of the patient and the task. In this view training to reduce compensatory movements as much as possible might not always be adequate for daily life, and we see signs of this in our data. These results show that one can be effective with an obvious compensation strategy. Therefore, it might be that training should rather be directed towards most functional movements for the type of task, taking into account the residual functions and characteristics of the user in order to determine the acceptable and necessary extent of compensatory movements that are adequate in order to train that user to be as skilled as possible.

Differences between the participants were also seen in the gaze behaviour. This part of behaviour has to our knowledge never been reported previously in prosthesis use. The lack of proprioceptive feedback means that prosthesis users presumably have to rely on vision so gaze behaviour would seem to be an obvious informative measure for the quality of prosthesis control. Overall, two types of gaze behaviour were observed in this study. The first type was to look continuously at the object during execution of the task, which is a gaze strategy that is generally observed in handling of objects in daily life tasks.[168] The second type of behaviour was to switch the gaze back and forth between the object and the prosthetic hand. The latter monitoring of the hand indicated that the participant needs to guide the prosthetic hand visually. It was expected that users who were less skilled in handling the prosthesis would show more monitoring of the hand during action performance, as was the case for P6. However, P2 also showed this behaviour but was relatively highly skilled in handling the prosthesis. Since P2 and P6 were the two participants who did not use the myoelectric prosthesis much during the week, gaze behaviour might be related more to the duration of use rather than to the functional abilities. It is worth noting that, despite the lack of proprioception, the gaze in all participants was directed towards the object for the most of the time. However, it is important to bear in mind that all participants were experienced prosthesis users. It would be interesting to examine gaze behaviour throughout the rehabilitation process. It is expected that the amount of visual attention to the prosthetic hand would be higher at the start, and will diminish throughout the rehabilitation process. This measure would be an indication of how the skills of the user develop over time.

Overall, the results of the different measurements were in agreement with each other and also complemented each other, as each of the more fundamental measures provided deeper insight in the performance of the participant on SHAP and thus, in the skills of the participants. However, an important question arises: When is a prosthesis user a 'skilled user', and how should skill level be defined? Bernstein[1] (one of the pioneers in the field of motor control), had a very clear vision and definition of skill (see also Latash and Latash[2]). In this final part of this discussion his ideas were used to meet the third objective of this study: To identify specific parameters that define skill of prosthesis users. Bernstein defined skill, or dexterity, as "the ability to find a motor solution for any situation, that is, to adequately solve any emerging motor problem correctly (i.e. adequately and accurately), quickly (with respect to both decision making and achieving a correct result), rationally (i.e., expediently and economically), and resourcefully (i.e. quick-wittedly and initiatively)".[1(p228)] Bernstein emphasized that people differ in the amount of dexterity they develop; one person can be more dexterous than another. More importantly, dexterity can be trained; however, the amount of dexterity that can be trained is different for each person.

Furthermore, Bernstein argued that dexterity is not in the movements themselves, but rather in the interaction of the motor processes and perceptual processes with the environment. The more complex and unpredictable the environment and the tasks are, and the better a person performs in that specific situation, the higher the person's dexterity.[cf 169] These insights are applicable to the performance of the participants in the present study. SHAP is a functional test with very complex tasks, especially in the ADL part of the test. Moreover, picking up a compressible object is complex, as the participant not only has to pick up the object, but at the same time has to try not to compress the object. On top of that, participants also had to manipulate the object by pulling off the Velcro, while trying not to squeeze the object. This study showed that some prosthesis users differed substantially in performance on both SHAP and the grasping tasks. Therefore we concluded that the better performers are more dexterous, and therefore more skilled, since they were more capable to interact with the changing and demanding environment. In light of Bernstein's definition of dexterity, we found that participants with a higher performance executed the tasks 1) more correctly: they were able to finish all SHAP tasks and compressed the deformable objects less; 2) they executed the tasks quicker; 3) they performed the tasks more rationally with adequate ranges of motion and visual guidance; and 4) they performed more resourcefully, which was especially noticed in SHAP where we could see that the quicker a person knew how to perform a task, the better the performance of that person was.

Moreover, Bernstein argued that several movement characteristics predict performance in a set of movements. In this study, we have identified certain parameters that are characteristics of skills in prosthesis use by means of the correlations between the different measures. The one parameter that was seen throughout the whole performance was time: the time needed to execute the tasks in both the clinical test and in the various dependent variables of the fundamental measures. This time is what Bernstein defined as quickness, which features importantly in his definition of dexterity, hence, in rehabilitation it is worth to spend time on quickness because it can lead to substantial improvement.[1] Therefore, we suggest to particularly focus on the time aspect of movement execution during the training to increase skill level of a patient. An important parameter determining the time of a grasping movement with a prosthesis is the plateau phase in the grasping profile (see also Bouwsema et al.[75]), which reflects the coupling of hand opening and closing.[170] This parameter showed the highest correlation with SHAP scores. Therefore, we argue that prosthesis training should focus specifically on reducing the duration of the plateau phase. By training coordination of hand opening and hand closing which will reduce this plateau phase, not only control of the different signals to open and close the hand would be improved, but, moreover, movements will look more natural. The quicker a prosthesis user will be with the prosthesis, the better and therefore more skilled his or her performance will be. As a result, the prosthesis probably will be used more frequently and with more satisfaction in daily life.

Conclusion

In this study, we measured prosthesis use on different levels of description, using clinical and kinematic measures. This study followed and extended the suggestion to combine several outcome measures as discussed in the introduction, by not only measuring on a clinical, functional level, but also on more kinematic levels. The results provided a wide range of information. The clinical test (SHAP) was a good measure of skill level of the prosthesis user, whereas the fundamental measures provided deeper insight into the performance and skill level of the prosthesis users. Participants who scored higher on SHAP showed less deviation in endpoint kinematic profiles from sound movement patterns, with, among other factors, shorter movement times, higher peak velocities, and shorter plateau times in the aperture. Moreover, they showed a better grip force control and less visual attention to the hand. The results show that time is a key parameter in prosthesis use, and should be one of the main aspects to focus on in rehabilitation. The insights provided by this study are useful in rehabilitation, because it allows therapists to specifically focus on certain parameters, such as plateau time or the visual control, which will hopefully result in the highest level of skills that can be achieved for that prosthesis user.

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the experiment. This study was approved by the local institutional review board (REB application 2010-099). An informed consent was signed by each participant before the start of the experiment. The authors plan to inform participants of publication of this study.

7

The role of order of practice in learning to handle an upper limb prosthesis

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Abstract

The objective of this study was to determine which order of presentation of practice tasks (random or blocked) had the highest effect on using an upper limb prosthetic simulator. 72 Healthy participants were randomly assigned to 1 of 4 groups, each composed of 9 men and 9 women. 36 Participants used a myo-electric simulator and 36 participants used a body-powered simulator. On day one the participants performed 3 different tasks in the acquisition phase. On day two the participants performed a retention test, followed by a transfer test with 3 new tasks. For each simulator there were four groups of participants: group 1 practiced random and was tested random, group 2 practiced random and was tested blocked, group 3 practiced blocked and was tested random, and group 4 practiced blocked and was tested blocked. Main outcome measures were initiation time, the time from the starting signal until the beginning of the movement, and movement time, the time from beginning until end of the movement. Although both groups improved significantly during the acquisition phase (p = .000), the blocked group had faster movement times (p =.009), and the learning extended over the complete acquisition phase. However, this advantage disappeared in the retention and transfer tests. Compared to a myoelectric simulator, movements with the body-powered simulator were faster in acquisition (p =.004) and transfer test (p = .034). Performance in daily life with a prosthesis is indifferent to the structure in which the training is set up. However, since practicing in a blocked fashion leads to faster performance, practice tasks should be presented as blocks in rehabilitation.

Introduction

People with an upper extremity amputation often choose to have fitted a prosthesis, but do not always use this prosthesis much in their daily life. Twenty to 40% of upper extremity amputees do not use their prosthesis at all due to a low degree of functional use.[6,171,172] The functional use of an upper limb prosthesis is not only determined by its function, that is, the technical possibilities, but also by its functionality, the way the amputee is able to handle the prosthesis. As has been shown previously, the latter aspect can be enhanced by training.[18,19] Consequently, by enhancing the functionality through training, the functional use of the prosthesis might increase.

Although the current training methods in the rehabilitation of upper limb amputees appear effective, there seems to be room for improvement. For instance, Fraser[173] showed that people do not use their prosthesis in everyday life as they have been trained to. He found that while training of prosthetic use focused on learning to manipulate objects, amputees used their prosthesis only for support while using their sound hand for manipulation. This, combined with the high rate of non-use, indicates that the effectiveness of current training can be increased. Moreover, it is known that quality of training determines the use of the prosthesis for the rest of ones life.[20] Therefore, training methods have to be developed in a way that functionality in everyday life will improve.

Several aspects of a training scheme can contribute to the efficiency of the training. The contents of the training are important in particular, by which we mean the different tasks amputees have to practice. Another important aspect is the structure of the training, which regards the design in which practice tasks are presented. The structure of the training might be particularly relevant to improve the transfer of skills to tasks in daily life. But what kind of training structure would most facilitate transfer to other skills and produce the greatest benefit for amputees? A concept often used to classify training structures when learning new skills is contextual interference (CI), which refers to the effect of the degree of interference of order of practice on learning.[174] A low CI involves practicing all trials of one task before the next task is introduced, commonly referred to as blocked order. High CI involves practicing the trials of each task in random order.[98] In general, studies prove that practicing skills under high CI—random order—enhances performance in transfer to other skills compared to practicing under low CI—blocked order.[98,99] Although most studies support the CI effect[99] of enhanced performance in other skills when practiced in a random order, there is limited knowledge whether the concept of CI does apply to learning to handle an upper limb prosthesis.

Weeks, Anderson and Wallace[19] examined the practice schedule that elicited the greatest degree of learning in the training of an upper limb prosthesis using the concept of contextual interference. In their experiment they used a body-powered prosthetic simulator to study learning and transfer of prehension skills under low and high CI. Results showed that the participants who practiced in a random order outperformed the participants who practiced in a blocked order. This effect of CI was present in the transfer test, but absent in the retention test. The latter unexpected lack of the CI effect can probably be explained by the design of the blocked schedule Weeks, et al.[19] used during the acquisition phase; the schedule they used for the blocked condition was repeated on two days, implying that this condition was not strictly blocked. Using a similar schedule, Tsutsui et al.[175] investigated the CI-effect with a bimanual coordination task and showed also a lack of a CI effect. Tsutsui et al. [175] reran their experiment comparing a strictly random with a strictly blocked order, and then did find an effect of CI. This indicates that an overall effect of contextual interference should be present if the order of practice is strictly applied. Thus, the lack of a CI effect in the study of Weeks et al.[19] might come from implementation of the blocked schedule. A key question of the present study is whether a CI effect can be found in learning to handle an upper limb prosthesis when the practice schedules are strictly applied.

The purpose of this study is to determine which order of practice tasks has the highest effect on performance with an upper limb prosthesis. We therefore examined training with two types of prosthetic simulators, myo-electric and body-powered, using the concept of contextual interference in a strict order. It was hypothesized that random practice with the simulators would lead to better results in retention and transfer than blocked practice.

Methods

Participants

Seventy-two students (36 men and 36 women, mean (SD) age: 21.07 (2.32) years) volunteered to participate. All participants were right-handed, had normal or corrected to normal vision, and had no restrictions of the right arm or hand. The participants signed an informed consent and were randomly assigned to 1 of 4 groups, each composed of 9 men and 9 women. Group 1 practiced random and was tested random (RR), group 2 practiced random and was tested blocked (RB), group 3 practiced blocked and was tested random (BR) and group 4 practiced blocked and was tested blocked (BB). 36 Participants used a body-powered prosthetic simulator, and 36 participants used a myoelectric prosthetic simulator in the experiment. The study was conducted in compliance with the tenets of the Declaration of Helsinki for research in human subjects.

Apparatus

Two simulators were developed to closely resemble a body-powered and a myo-electric upper limb prosthesis for a below-elbow amputation (Figure 7.1).

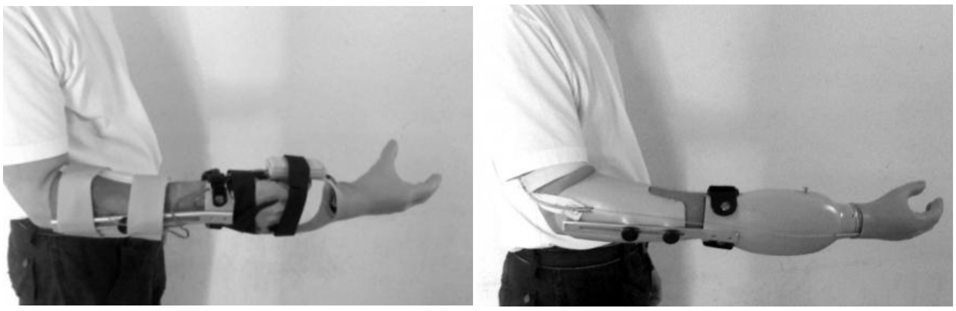

Figure 7.1 *The body-powered simulator (A) and the myo-electric simulator (B).*

Each of the simulators consisted of a conventional prosthetic hand (Otto Bock®) attached to an open cast in which the hand could be placed. The cast extended into a splint along the forearm, adjustable in length. The splint could be attached to the arm using a Velcro sleeve. To mimic a prosthesis as closely as possible the sound hand was left unattached, to prohibit facilitating control of the prosthesis. The hand of the body-powered simulator was connected to a cable, attached to a harness system fitted around the contra lateral shoulder. This harness was adjustable, to create an appropriate tension of the string to open and close the hand with motions of the torso, shoulders and arm. The myo-electric simulator was powered and controlled by changes in electrical muscle activity, detected by two electrodes placed on the dorsal and palmar flexors in the lower arm. The electrodes were placed at the inside of the Velcro sleeve, and subsequently controlled an electric motor in the hand. Hand opening was accomplished by activity of the dorsal flexors, while the hand closed by activity of the palmar flexors. Participants were instructed not to move their hand during operating the prosthesis.

A task board, (60 x 60 cm) fixed to a table, indicated the start and end positions of the tasks. All tasks were started and finished by pressing the space bar of a keyboard, which was used as a start/stop button. The keyboard was positioned at the right of the participant, at 30 cm from the midline and 3 cm from the edge of the table at which the participants were seated. The task to be executed was presented on a computer screen, positioned at the left side of the table at the beginning of every trial.

Design

On the first day, the participants had to execute 3 tasks, each consisting of 20 trials. The order of practice was either random (R) or blocked (B), with task order in the blocked schedule counterbalanced within groups. On the second day, a retention test and a transfer test were conducted to determine the effect of learning from the previous day. In two groups, BR and RB, the order was changed. The retention test consisted of 5 trials of each acquisition task, while in the transfer test 5 trials of three new tasks had to be executed.

Procedure

The participants were allowed to test the simulator once—opening and closing the hand in mid-air—to check whether it was operating correctly. No further practice was allowed. After the participants were seated, the tasks were explained and the participants were instructed to perform each trial as rapidly and accurately as possible. Each trial started with depressing the space bar of the keyboard. To signal the start of the task an auditory tone was given at a random interval of 0 to 4 seconds. A trial was finished as soon as the participants completed the trial and pressed the space bar again. When a trial was not executed properly, that is, when an object was knocked over or dropped, the trial was repeated immediately.

Tasks

The tasks used were based on field research by Van Lunteren et al.[89] This study revealed that people used their prosthesis in three different ways; direct grasping, indirect grasping and fixating. For each of these actions, a task was designed that was used in the acquisition phase and retention test, and other tasks that measured the same use of the prosthesis were devised for the transfer test.

The tasks in the acquisition phase and retention test were simple laboratory tasks to learn how to handle the simulator. In the pick up task, which resembled direct grasping, a wooden cylinder of 4 cm diameter and 10 cm height had to be picked up from the start position with the prosthetic hand and had to be placed at the end position. The start position was located 23.5 cm from the edge of the table, 55 cm left of the space bar, and the end position was located 25 cm at the right and 30 cm behind the start position. For indirect grasping, the hand-over task was designed. The same wooden cylinder was held by the sound hand at the start position. After the start signal, the cylinder had to be handed over to the prosthetic hand and had to be placed at the end position. The same starting and end positions were used as in the pick up task. In the ruler task, a fixating task, a ruler of 30 cm had to be placed and fixated over two points with the prosthetic hand, and a straight line had to be drawn between these points with the sound hand, over a distance of 19 cm. The points were presented on a sheet of A4 paper, fixed to a document holder that made an angle of 30 degrees with the table.

The transfer tasks resembled the learning tasks, but were based on activities in daily living, and therefore more complicated. In the pick up mug task, a mug had to be picked up at the ear from the starting position with the prosthetic hand and had to be placed on the end position. The starting position was located 30 cm in front of the participant, in line with the shoulder, and the end position was situated 20 cm in front of the starting position, and 30 cm above the table on top of a box (as if the mug was placed on a shelf). This task resembled the pick up task. In correspondence with the hand-over task, the lid off jar task was designed. The 5x13 cm jar was held by the sound hand at the start position and had to be handed over to the prosthetic hand after the start signal. Subsequently, the lid had to be removed by turning it with the sound hand and placed at the starting position, while the jar had to be placed at the end position with the prosthetic hand. The same starting and end positions were used as in the hand-over task. The sharpener task was chosen as a fixation task. Before every trial, a pencil was already inserted into a mechanical sharpener. While fixating the sharpener with the prosthetic hand, the crank had to be turned 3 times with the sound hand to sharpen the pencil. The sharpener was located at the midline at 23.5 cm from the edge of the table.

Data analysis

E-prime was used to register the initiation time (IT) and movement time (MT), recorded in milliseconds. IT was the time between the auditory tone and the release of the space bar. MT was the time between the release of the space bar and the return to the space bar at the end of the trial.

To compare the performances of the groups on the different tasks, z-scores were calculated for each task separately in the acquisition phase, the retention test and the transfer test. The acquisition trials were then grouped in 4 blocks of 5 trials, and a mean z-score was calculated for each block. A negative z-score implied performance faster than the mean.

Separate analyses were executed on IT and MT in each of the phases. For the acquisition, a repeated measures ANOVA was executed, with prosthesis (myo-electric versus body-powered) and group (B versus R) as between-subject factors and block (1, 2, 3 and 4) and task (pick up, hand over and ruler) as within-subject factors. The scores of the retention test and transfer test were subjected to separate repeated measures ANOVA's, with prosthesis (myo-electric versus body-powered) and group (RR, RB, BR, and BB) as between subject factors and task (mug, jar and sharpener) as within-subject factor. When Mauchly's test indicated that sphericity was violated, the degrees of freedom were adjusted with the Greenhouse-Geisser correction. In all analyses a significant criteria of $\alpha \leq .05$ was used, and post hoc tests on main effects used Bonferroni correction.

Results

Initiation Time

The ANOVA for IT in the acquisition phase indicated no significant main effects between groups, between simulators or among tasks. However, a significant main effect of block ($F_{1.809, 123.04} = 3.45$; $p = .039$) was detected. Multiple comparisons showed a significant improvement in performance between block 1 and block 2 ($p = .010$). Also, a significant interaction effect of task by block was detected ($F_{4.57, 310.47} = 2.46$; $p = .038$); the participants improved more in the indirect grasping task than in the direct grasping or the fixating task. The means of all significant main effects are combined in Table 7.1.

Table 7.1 Mean z-scores and 95% confidence interval for the significant main effects.

Dependent Variable	Phase	Factor	Level	Mean z-score	95% CI*	
					lower	upper
Initiation Time	Acquisition	Block	1	.091	-.064	.247
			2	-.037	-.199	.125
			3	-.038	-.203	.126
			4	.026	-.160	.212
Movement Time	Acquisition	Block	1	.543	.387	.699
			2	-.023	-.162	.115
			3	-.155	-.288	-.022
			4	-.259	-.389	-.130
		Group	Random	-.149	-.333	.035
			Blocked	.202	.018	.386
		Simulator	Body-powered	-.171	-.355	.013
			Myo-electric	.223	.223	.407
	Transfer	Simulator	Body-powered	-.137	-.002	.406
			Myo-electric	.191	-.352	.008

* CI, confidence interval

The ANOVA for IT in the retention test indicated no main effects or interactions.

The ANOVA for IT in the transfer test also indicated no significant effects.

Movement Time

The ANOVA for MT in the acquisition phase indicated a significant main effect of block ($F_{2.09,\ 142.30}$ = 148.36; p = .000). Multiple comparisons revealed that this improvement in performance was significant over all four blocks of the acquisition phase (all *p's* <.01) (see Table 7.1). A significant effect of group ($F_{1,\ 68}$ = 7.25; p = .009) indicated that the blocked group had faster MTs than the random group. We also found a significant main effect of simulator ($F_{1,\ 68}$ = 9.12; p = .004). The participants with the body-powered simulator executed the tasks more quickly than the participants with a myoelectric simulator. No main effect of task was detected. A significant block by group interaction ($F_{2.09,\ 142.30}$ = 8.07; p = .000) indicated that the blocked group kept improving during the acquisition phase while the learning curve of the random group flattened (see Figure 7.2). A significant task by block interaction ($F_{3.88,\ 262.31}$ = 3.25; p = .014) revealed that the participants kept improving in both the grasping tasks during the acquisition phase, while the fixating task leveled off.

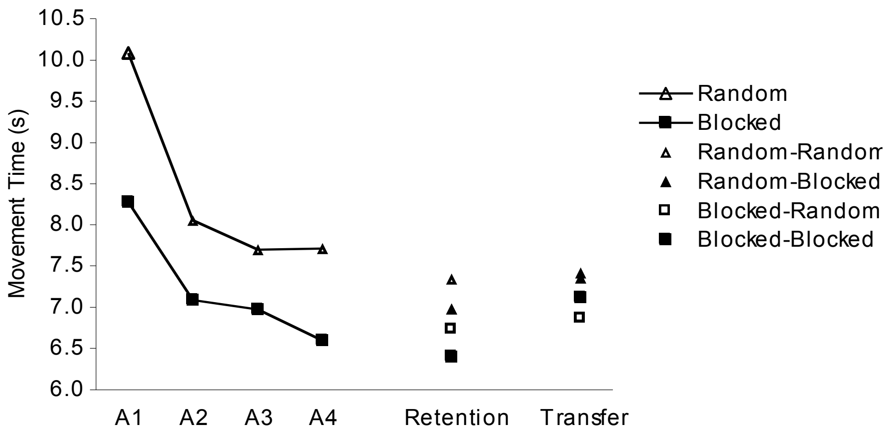

Figure 7.2 *Movement time in seconds for each of the two groups (random (R), blocked (B)) in the four blocks of the acquisition phase (A1, A2, A3, A4), and for the four groups (RR, RB, BR, BB) in the retention test and transfer test. Means are collapsed across tasks, because there were no significant main effects of task.*

The ANOVA for MT in the retention test indicated no significant main effects among groups, between simulators or among tasks. The only detected significant interaction was task by simulator ($F_{1.31,\ 83.96}$ = 5.04; p =.019). Both types of simulators had comparable movement times for the direct grasping task. However, for the other two tasks, indirect grasping and fixating, movement times with the body-powered simulator were faster than with the myoelectric simulator.

The ANOVA for MT in the transfer test indicated no significant main effects among groups or between tasks. However, a main effect of simulator was present ($F_{1, 64} = 4.69$; $p = .034$) showing that tasks with the body-powered simulator were executed faster than with the myoelectric simulator. No interaction effects were significant.

Discussion

The purpose of this study was to determine which order of practice tasks had the highest effect on performance with an upper limb prosthesis. Two groups practiced tasks either in a random or in blocked order to examine order effects on learning in an acquisition phase, which were tested with a retention test and a transfer test. Although both groups improved during the acquisition phase, the blocked group performed faster than the random group, and the learning extended over all phases of the acquisition. However, the positive effect of the blocked training did not turn up in the retention test and the transfer test, implying that the order of practice does not influence the performance after training or the performance of tasks other than trained.

The clinical implication of this finding is that in terms of practice effects none of the two tested orders of practice is preferred over the other. However, since practicing in a blocked fashion leads to faster performance, we advice practice tasks to be presented as blocks in rehabilitation setting. In a blocked schedules people learn more quickly how to handle the prosthesis, and such steady improvement can motivate the trainees to pursue the training.[9] Moreover, in rehabilitation settings the amount of training time is restricted. By practicing in a blocked rather than a random order, a trainee can perform more trials in the training time, which should result in enhanced learning.[100]

We found a clear advantage of blocked practicing on speed of performance in the acquisition phase, but—although expected form a contextual interference (CI) effect—this advantage was not found in retention and transfer. This finding is remarkable since most studies support the overall effect of CI.[99] A possible explanation of the lack of CI effect in this study can be found in the work of Magill and Hall.[98] They stated that the CI effect will not be found when only one motor program is involved in the practice tasks. A motor program serves as a representation of a class of movements. In the schema theory of Schmidt[15] the invariant characteristics of a given class of movements are stored in a motor program. Specific movements are possible by adding variant characteristics to the invariant characteristics of the motor program, according to Schmidt.[176] As such, movements with the same invariant characteristics belong to the same movement class and are therefore controlled by the same motor program.[176] Magill and Hall[98] hypothesized that learning tasks within the same motor program is less difficult than learning tasks which are controlled by different motor programs. Therefore, the CI effect will not be found when tasks are practiced within one motor program.[98]

The notion that practicing tasks within a similar motor program does not result in CI effects[98] might explain the discrepancy between the results of Weeks et al.[19] and our study. Although we replicated parts of the study of Weeks et al.[19], we also introduced some changes. Besides the use of two different types of simulators, we used different types of tasks. We based our tasks on the actual use of prosthesis in daily life, as found by field research of Van Lunteren et al.[89] They showed that people used their prosthesis in three different ways; direct grasping, indirect grasping and fixating. For each of these three actions, we designed tasks for the learning and test phases. This implied that the underlying essentials of the transfer tasks resembled the learning tasks closely, although the transfer tasks were more complicated. The transfer tasks involved more submovements than the learning tasks because these tasks were based on activities in daily living. The underlying similarity in the learning and transfer tasks might have resulted in using the same motor program for these tasks, and therefore, we did not find an effect of CI.[98] On the contrary, the tasks Weeks et al.[19] used in the transfer test differed from the practice tasks, because the similarity was only based on general characteristics of the tasks, as bilateral nature and fine manipulation. These tasks might presumably be based on different motor programs, and therefore they did find an effect of CI.

Considering the outcome of our study, we would like to push this reasoning one step further. Magill and Hall[98] also suggested that when only one motor program is involved in practicing, a mixed schedule (blocked practice followed by random practice) would lead to better learning than only practicing in a random or a blocked order. Although the current experiment was not designed to test this hypothesis, the results suggest that these processes are at work during learning to handle an upper limb prosthesis. Although not significant, the means showed that the blocked-random group had the lowest initiation times in the retention test and the transfer test, and also the lowest movement times in the transfer test. Furthermore, Proteau et al.[100] indicated that when participants first practiced in a blocked order and then in a random order, the advantage is that they learn more quickly because of the blocked order, and the following random order will also promote transfer to skills other than learned. If blocked-random will be the preferred training order, this may have further implications for the rehabilitation settings. Then, a rehabilitation program will have to be built of two segments: a blocked part in which the amputee learns the quickest how to handle the prosthesis, and a successive random practice part preparing the amputee for performing the activities in daily living. Future investigations should examine whether this order will elicit the best training results.

In addition to the main result as discussed above, the type of prosthesis did affect performance. Participants with the body-powered simulator had faster movement times than the participants with the myo-electric simulator. This difference could imply that it is easier to learn to handle a body-powered prosthesis. Another possibility is that the body-powered prosthesis is simply easier to handle than the myo-electric prosthesis, based on the construction. Although comparisons have been made between the myoelectric and the body-powered prosthesis using questionnaires,[4] the differences between these prostheses have never been investigated using performance measures. The current study is not up to the task to determine the origins of the difference between the prostheses. At this point we just want to emphasize this performance difference. We are setting up future research to examine more closely the difference in performance with both types of prostheses.

Finally, an important aspect of the current study that deserves further attention was the use of prosthetic simulators—worn by healthy participants—instead of real prostheses— worn by amputees. A major disadvantage of a simulator is the overlength of the arm, since the prosthetic hand is placed in front of the sound hand. This changes the movements slightly from movements executed with a real prosthesis, because the shoulder has to be retracted to keep the same length of the arm compared to the sound arm. This is especially the case in the indirect grasping and fixating tasks. Another, perhaps even more important, aspect is that the somatosensory cortical representation presumably changes after limb amputation.[177] This change, which is not present in our participants, could influence the learning process while learning to handle a prosthesis. However, despite these limitations of the simulators, note that using simulators also involves some major practical advantages. Important is that we do not have to bother amputees who have just sustained an amputation. Another advantage is that we can test more participants, and we do not have to rely on the few recently amputated patients. However, further research is needed to establish the generalization of our findings with the simulators to the amputee population.

Conclusion

Performance in daily life with a prosthetic device is indifferent to the structure in which the training is set up. However, since practicing in a blocked fashion leads to faster performance, practice tasks should be presented as blocks in rehabilitation.

Acknowledgements

We thank Marieke van der Steen and Kirsten Huls for their help running the experiment. We thank Johan Horst for the design and construction of the prosthetic simulators.

8

General Discussion

The studies performed in this thesis aim to increase our understanding of the learning processes during skill acquisition of upper-limb prosthesis use. This final chapter will combine the results from the different studies, allowing identification of evidence-based components of training. The results will be discussed based on the phases of the prosthesis rehabilitation process. In the Appendix, the identified evidence-based components are combined in a training guideline for myoelectric prosthesis users.

Preprosthetic phase

In the preprosthetic phase it is important to train the control of the myoelectric signals originating from the muscles,[1,2] which will provide a higher skill level for the use of the prosthesis at the beginning of the prosthetic phase. An adequate control of the muscles, i.e., correct, proportional, and independent contractions, is imperative for a good control of the prosthetic hand.[1,3] In *Chapter 3,* three types of training have been studied to determine which method exhibited the strongest learning effect on the myoelectric control. Able-bodied participants trained opening and closing of either a practice hand, a prosthetic simulator hand, or a virtual prosthetic hand. Results showed that all training types led to similar results in performance; virtual training of hand opening and closing was as good as training with a real hand. Thus, for overall performance in the preprosthetic phase it does not matter in which method is utilized and a choice therefore may be based on different grounds. Below a number of important practical and financial advantages of a virtual approach will be discussed, leading to a preference and recommendation for covering a considerable part of the training in the preprosthetic phase by virtual training.

Using virtual training in the rehabilitation of prosthesis users

Virtual training is a simulation of the real world with an interaction between the human and a machine. It is often used in areas of work and rehabilitation, such as in rehabilitation of neurological patients.[4] Virtual training is increasingly becoming the subject of study in the field of prosthetics; several research groups are working on the development of virtual environments.[5] Virtual reality creates attractive environments in which control can be practiced through play, which motivates to practice. Moreover, practicing with a serious game creates an external focus on the intended outcome of the movement, which leads to a more effective learning compared to an internal focus of attention on the movements of the body.[6,7] Other advantages are that a virtual environment is easy to manipulate with respect to difficulty, feedback can be provided easily and it is cost efficient as it can be practiced without the presence of a therapist all the time.[8-10] Moreover, provision of the most appropriate prosthesis is important because an inappropriate choice of prosthesis could lead to non-acceptance and non-use. Trying out different types of prostheses and settings is therefore very useful and doing this virtually is financially attractive, because it can be easily done, whereas it is expensive to have many prototypes available to try on each patient.

To date, the virtual environments that are developed in the field of prosthetics have only been tested in laboratories, and have yet to be launched onto the market. However, before virtual training can be widely used in the rehabilitation of prosthesis users, a fundamental question needs to be answered: does transfer occur from the human-machine-interaction to human-environment-interaction? Do the skills that are learned in the virtual environment transfer to the real world situation of handling the prosthesis in everyday life? *Chapter 3* and *Chapter 5* provide tentative evidence that the virtually learned control of the myoelectric signals and grip force can in fact transfer to the real prosthetic situation. However, these studies were executed in an isolated situation, and handling a prosthesis in interaction with the environment was not tested. Although most studies, including the ones in the field of prosthetics, assume that training in virtual reality will transfer to real life, conclusive evidence has not been provided yet. There is thus a need for thorough investigations towards the transfer of virtual environments to real world situations.[11-12] Important to know is what exactly is being transferred, in order to be able to develop virtual environments that facilitate real world skill improvement.

Ability of skill learning

An interesting finding of the study in *Chapter 3* was the difference amongst participants in their learning ability of proportional control of the myoelectric signals. It is generally known that people differ in their ability to learn new motor skills.[13-15] But this has never been taken into account in literature on prosthetic training. A division was made in *Chapter 3* between people that were able to make a good distinction between different velocities of hand opening and hand closing, so-called high capacity learners (HCL), and people who could not make this distinction, low-capacity learners (LCL). The LCL were less able to vary the myoelectric signals and had therefore a lower proportional control compared to the HCL. The difference in learning of the two groups may have two different causes. It might be that the acquisition of skills was slower for the LCL than for the HCL. The training only lasted for three sessions, and they might need more training to achieve a better proportional control. A second explanation would be that the LCL were less skilled, and would never develop a high level of proportional control. The second explanation is supported by the results of *Chapter 6,* in which considerable differences were found between the performance levels of six experienced prosthesis users, both in kinematics as well as in a functional test.

Individual differences in motor control have not been widely studied in the literature.[16] Yet, from early in life, there are differences in the development of motor skills and movements between people.[16] It is generally known that some people become more proficient in certain motor skills, like sports or playing an instrument, than others. Bernstein, an important scientist in the field of motor learning and motor control[14,17] argued that there are individual differences in the amount of skill, or dexterity as he called it, one can develop. He indicated that it is different for each person to what extent a skill can be trained.[14] While most studies on individual differences[15,18] suggest that cognition plays an important role in skill learning, King et al.[16] suggest that the differences in how people perform a movement might originate from having preferred movement strategies which influence the learning process of tasks. Further studies on the learning process and the movement strategies used during learning to control myoelectric signals, might shed more light on the learning ability of prosthesis users. This knowledge should be taken into account when designing a prosthetic training program. When early in the rehabilitation it is known whether someone has a high or a low ability to learn certain skills and to what level skills can be trained, the prosthesis user can be provided with the best individualized care. This might be possible with a test that assesses and predicts these abilities. However, such a test is not available yet. In a recent, not yet submitted study, our research group has examined the relation between skill level in myoelectric control reached by participants and their performance on simple dexterity tests. Results revealed that dexterity tests did not predict the performance in myoelectric control. According to Adams,[18] motor skills are highly specific and therefore do not correlate well with overall simple motor tasks such as dexterity tests. This means that performance on a certain task can only be predicted by the performance on the task itself.[18] It would be interesting to study whether a test that assesses early performance in myoelectric signals control would be a good determinant to predict learning ability and end level of skill in myoelectric control.

Training programs would benefit from the development of a test that is able to discriminate between fast and slow learners, and the motor capabilities of a person. Such a test would influence two important aspects in the rehabilitation process of prosthesis users. Firstly, training schedules can be individualized to the motor learning ability to achieve the best level of control. Secondly, the selection of a prosthesis depends on the ability to control the myoelectric signals. Several types of myoelectric prostheses are available. Conventional myoelectric prostheses have a motorized hand that allows for opening and closing of the hand in a tripod grip. Additional features such as a wrist rotator or a flexible wrist can be added which increases the movement possibilities of a prosthetic hand. Recently, even more advanced multi-articular hands became available on the market such as the i-Limb from Touch Bionics, the BeBionic from RSL Steeper, and the Michelangelo Hand from Otto Bock. These hands have more functions than the conventional hands and allow several grip patterns to be selected. Although additional features and more advanced prostheses increases the function of a hand, at the same time they pose higher demands for the ability to control, since the same myoelectric signals are used for all functions. An advanced prosthesis with many features would have no use for someone who does not have a high ability to control the prosthesis, and might only lead to frustrations and rejection of the prosthesis. Such a low ability learner might be better off with a simpler prosthesis. Meanwhile, a person who is able to develop high prosthesis skills might benefit from an advanced prosthesis in comparison to a simple prosthesis.

Prosthetic phase

The studies in this thesis focused on three main actions that can be performed with a prosthesis. Indirect grasping, in which the unaffected hand presents an object to the prosthetic hand, and fixating an object using the prosthetic hand or arm. Both are commonly performed by prosthesis users.[19] Direct grasping, in which the prosthetic hand grasps an object directly without the use of the other hand, which is performed less often by prosthesis users.[19] Nonetheless, this action is studied as well because it allowed us to compare the movements with able-bodied prehension that is known from literature on the one hand, and on the other hand this action should be performed by prosthesis users at least as often as the other actions when they have learned to control the prosthetic hand dexterously. The focus in the studies has been mainly on the unilateral control of the prosthetic hand, which is necessary to improve functionality with the prosthesis. However, an average user uses the prosthetic hand only 30% of the time for one-handed activities,[20] hence it is important to incorporate ambidextrous actions in the rehabilitation process as well.[21] The deliberate choice to focus mainly on the performance of the prosthetic hand in this thesis allowed us to identify aspects that require attention with regard to training of the prosthesis side. These aspects are further discussed in the following subparagraphs.

Coordination of reaching and grasping with a prosthesis

In *Chapter 2* prehension was studied in prosthesis users in order to highlight specific components in the movements that are characteristic to prosthesis use, which ought to be an important focus during the rehabilitation process. Performance of experienced prosthesis users was compared to movements made with able-bodied sound hands that are known from literature. Prehension in sound hands has been amply studied[22,23] and enables comparison of the kinematic profiles to the profiles found in prosthesis users. Prehension with the prosthesis was characterized by longer movement times compared to an unaffected upper-limb. Moreover, movements were performed less smoothly, and the timing of the various elements of the movements was different. Reaching and grasping with the prosthetic hands were uncoupled as opening of the prosthetic hand started later than the reach and did not close until the reaching movement was over, while reaching and grasping are well timed in able-bodied hands. Also, a plateau phase was present between hand opening and hand closing in the prosthetic hand (see Figure 2.1 in *Chapter 2* and Figure 3.4 in *Chapter 3*). This plateau was already found by Fraser and Wing[24,25] in a body-powered prosthesis user, and has been found to be a characteristic of myoelectric prosthetic grasping in *Chapter 2, Chapter 4,* and *Chapter 6* of this thesis. A possible explanation for the overall delay in timing might be the lack of sensory information. A prosthesis user gets less natural feedback about the actions performed with the prosthesis in comparison with an unaffected hand, and must therefore rely primarily on vision. As vision is slower than proprioceptive feedback[26] all processes take longer to ensure successful performance of the actions (see also *Chapter 2*).[24,25] Two concrete recommendations could be put forward for training from the results of *Chapter 2*. During training of grasping with the prosthetic hand focus should be on the timing between the hand opening and the hand closing. Furthermore, attention should be paid to the simultaneous ending of the reach and the grasp. When these aspects can be improved, the timing and the fluency of the movements will be better, resulting in shorter movement times and, thus, faster overall performance.

Gaze behavior

As the majority of sensory information such as proprioceptive and tactile information, is lost in prosthesis use, visual information is the main source of feedback still available. Whereas vision already plays a role in correcting movements in able-bodied prehension,[22] in prosthesis use the role of vision increases considerably. Prosthesis users often look at their prosthetic hand while performing actions with the prosthesis (*Chapter 6),* while when manipulating objects with an unaffected hand, the hand is hardly looked at but rather the object to be grasped or manipulated.[27] Although the reliance on visual information of prosthesis users is often reported in the literature, there are surprisingly few studies performed on the role of vision during use and learning to use a prosthesis. Only two other research groups have recently studied visual behavior in prosthesis use.[28-30] They found similar gaze behavior as reported in *Chapter 6,* and are currently working on coding schemes to enable assessing the visual attention during the use of upper limb prostheses in activities. *Chapter 6* reveals that more proficient prosthesis users looked less at their prosthetic hand. It can therefore be expected that the amount of gaze time that is spent on the prosthetic hand will reduce throughout the rehabilitation, as a novice user will likely look often at the hand, while it will be reduced when the user gains more proficient control of the prosthesis. Gaze behavior could therefore be included in the measures of performance to determine the skill level of the prosthesis user. Another tentative suggestion which could be extracted is that one could train to look less at the hand, which might accelerate the learning process. However, as long as prosthesis users do not have other sources of feedback, they will always remain dependent on the visual information. Therefore it cannot be expected that all actions can eventually be performed without visual control.

Feedback

The provision of feedback is important for the learning process.[31-33] The two main types of feedback a learner can receive are intrinsic and extrinsic feedback.[31] Intrinsic feedback is the sensory and perceptual information a person naturally receives when performing the task, such as touch. Extrinsic feedback is provided by an experimenter or therapist to augment some aspect of the performance. This complementary information can be provided to supplement the intrinsic feedback. This becomes especially important when the intrinsic feedback is partly absent as in prosthesis use. Over the years, research groups have tried to replace the lost sensory feedback with artificial information such as auditory, vibrotactile, or visual feedback.[34-36] However, to date, none of the methods developed have been built in the commercial prosthetic hands because they do not work properly enough yet.[37,38] Until there are developments that will provide prosthesis users with such forms of feedback, they have to cope with the only information that is still available to control actions: visual information.[39,40] For now, the visual feedback should therefore be exploited during training. In *Chapter 5* visual information was provided during virtual training of grip force. Two types of extrinsic feedback were tested for their contribution to learning, feedback on the movement execution and feedback on the end result of the movement. Results showed that the performance after training was better for the group that received feedback on the end result.

This is in accordance with most other studies that are performed on these two types of extrinsic feedback in able-bodied persons.[33]

Provision of information about the movement execution could make a learner become reliant on that feedback. This phenomenon is described in the guidance hypothesis.[41-44] Information about movement execution could provide too much information, which is detrimental to learning, because learners are not challenged to actively search for solutions to the problem.[45] Thus, *Chapter 5* shows that practicing with more information available might not always be beneficial to skill learning with a prosthesis. Rather, a learner would benefit more from information about the end result. For example, a therapist should specify how much an object is compressed rather than providing feedback on the amount of used muscle contraction and the speed of the hand closing when a learner picked up a compressible object. Too much feedback might prevent effective learning, therefore one should carefully deal with the provision of information.

Grip force control

A good control of grip force is one of the most difficult aspects of the prosthesis rehabilitation, and is one of the highest goals that can be attained during the rehabilitation process.[1] A good control of grip force is needed in everyday life in order to handle objects correctly without breaking it or dropping an object. Several studies with neurological patients who have no or only limited proprioceptive feedback[46,47] as well as studies with prosthesis users[48-51] have shown that people can have control of grip force to a certain extent despite the limited feedback that is available. In general, people are able to use visual information to predict their motor control, based on the learned information-movement couplings.[52-55] Moreover, it is known that people can retrieve aspects of the object´s affordances related to dynamics which allows them to use predictive control in object manipulation.[56,57] This prospective control is most likely used by the participants who trained indirect grasping in *Chapter 4*. They were able to scale their grip forces to the object's demands better compared to the group that trained direct grasping with the prosthetic hand. By handing over non-rigid objects from their unaffected hand to their prosthetic hand, they might have been able to retrieve aspects of the object, such as the compressibility, on the basis of the earlier grasps with the unaffected hand. It is therefore recommended to start with a task that requires indirect grasping when one starts to practice grip force control with non-rigid objects.

Chapter 5 shows that virtual training with extrinsic feedback on the end result improves the grip force control. Grip force control only improved in the test-tasks that provided information on the applied grip force. These tasks resembled the training in terms of the provided information, whereas the tasks in which an estimation of the applied force was required did not improve. This has been found in earlier studies as well.[39,58] It is therefore recommended to include estimating grip force in training as well, because a good control in those tasks is relevant as in daily life prosthesis users are not always provided with feedback on the applied grip force. Furthermore, *Chapter 5* shows that it is better to start with a task that allows for high force productions. In *Chapter 4* and *Chapter 5* it became apparent that learning the control of grip force in prosthesis use is a gradual process that takes a lot of time. Ample time will therefore be needed to achieve a good level of grip force control.

Structure of training sessions

Moving to an overall level of studying how training should be offered to prosthesis users, it is of interest to ask what kind of structure a training must have to achieve the highest effects of learning. A concept that is often used in the structure of training when learning new skills is the concept of contextual interference. Contextual interference refers to the influence of practice order on learning.[59] When practicing with a low contextual interference, one task is practiced to a certain level before the next task is introduced, also known as blocked practice. With a high contextual interference on the other hand, several tasks are practiced simultaneously in a random order.[60] It has been generally shown that random practice enhances performance in transfer to other tasks than learned.[60,61] In *Chapter 7* novice prosthesis users practiced in either a blocked or a random structure. No significant differences were found between the two structures of practice. Because blocked practice led to more rapid improvements early in training, it can be recommended to start practicing in a blocked fashion. This will motivate learners to continue to practice. Although not tested directly in the studies in this thesis, there are hints that a blocked-repeated fashion leads to the best performance. The group that practiced in a blocked fashion and was tested in a random fashion had the fastest performance during the test after training in *Chapter 7*. Moreover, indications were found in *Chapter 4* that practicing a combination of tasks in a blocked-repeated fashion leads to the best performance. In a blocked-repeated structure, blocks with different tasks were concatenated and then repeated, resulting in a quick learning because of the blocked practice in the beginning, followed by random practice of the blocks to promote transfer to tasks other than learned.[62]

Evaluation of performance and skill level

The duration of the rehabilitation process and the skill level reached during the rehabilitation depends on many variables, such as the amount of training, amputation level, type of prosthesis, learning ability and motivation.[63] No clear norm exists how much training is needed to handle a prosthesis dexterously, and when someone has reached their maximum skill level. *Chapter 6* focused on measuring prosthesis use on different levels of description to get insight in the determinants of skill level. Several outcome measures were combined, as recommended by the Upper Limb Prosthetic Outcome Measures (ULPOM) group,[64,65] although their recommendation was taken one step further. Taking the International Classification of Functioning, Disability and Health (ICF) model of the World Health Organization into account, performance was not only measured on the activity level of the prosthesis user, which is typically done in rehabilitation, but also on the level of body structures and functions, which relates to device performance and captures for example speed, grip force and range of motion.[64] This provided deeper insight into the performance and skill level of prosthesis users. An important question that is discussed in *Chapter 6* is when a prosthesis user can be called a 'skilled user' and how skill level should be defined. The ideas of Bernstein[14] were used to determine skilled prosthesis use. He defined skill, or dexterity, as "the ability to find a motor solution for any situation, that is, to adequately solve any emerging motor problem correctly, quickly, rationally, and resourcefully". In the light of this description, skilled prosthesis users were identified as the ones that performed the tasks more correctly with higher scores and better grip force control, quicker, more rationally with adequate movements and less visual guidance of the prosthetic hand, and more resourcefully. Time of movement execution, 'quickness' in Bernstein's terminology[14], was determined as a parameter that defines skilled prosthesis use. Especially the duration of the plateau in the grasping profile determines skill. The shorter the moment between hand opening and hand closing, the better the coordination between these two movements, the more skilled a prosthesis user is.

With the factors of skill level determined, it is also useful to know when someone has reached a certain skill level sufficient to terminate the rehabilitation process of a prosthesis. A number of indicators could be deduced from this thesis that might help to determine this. First, one could look at the change in learning over time. In the beginning, skill will improve quickly, while later on in practice the improvement rate slows down.[66-68] Although learning is never entirely finished, not even in simple tasks[67], one can determine the moment that the learning curve flattens and no significant improvements are made that are relevant for the rehabilitation process. To be able to monitor improvements it is important to perform regular evaluations throughout the rehabilitation process. A second indicator is the gaze behavior. The less the gaze is directed towards the prosthesis during task execution, the more skilled the user will likely be. A third aspect that might help to determine proficiency of the prosthesis user is to look at the timing and fluency of the movements made. More skilled users show faster and smoother movement patterns than less skilled users. Directions can be found in the immediate succession of hand closing after hand opening and the simultaneous ending of reaching and grasping. A fourth aspect is to look at the grip force control. A more proficient user will compress objects less than a less proficient user. In addition to the clinical tests that are used, these indications might help therapists to determine when someone has reached the end of the rehabilitation process.

Critical reflections

Several studies in this thesis examined able-bodied participants with prosthetic simulators instead of real prosthesis users. The use of simulators had several advantages. First of all, recently amputated patients were not bothered. It would not have been ethical to deny novice prosthesis users the regular occupational therapy in the early stages of exploring the learning processes. Moreover, we were not limited by the small number of novice prosthesis users. Many more participants could be included by using the prosthetic simulator, which improved the reliability of the studies.

There are some disadvantages to using a prosthetic simulator as well. Because the prosthetic hand was placed in front of the sound hand, the entire arm had an overlength. This changed the movements slightly from movements of real prosthesis users, because the shoulder had to be retracted to have the hands on the same level in space. A second disadvantage was that mainly young, healthy students were measured between the ages of 20 to 30 years. This group is not entirely similar to the average population of novice prosthesis users, which are mostly people in the working age.[69,70] In addition, only conventional myoelectric hands were studied. These hands have only one grip pattern, whereas the newly developed multi-articulated hands have more possibilities and grip patterns. The features of these new hands will presumably influence the movements made by the user, although the aspects described such as the coordination, feedback, grip force, gaze, and structure of the training are still present when using more advanced hands.

The clear differences to the real community of prosthesis users need to be considered when evaluating the findings in this thesis. Some level of caution must be used when applying the results to prosthesis users as it is not yet known whether the results can be generalized entirely. There are some indications that justify the use of able-bodied participants using prosthesis simulators. Schabowsky et al.[71] found similar learning skills in amputees as well as able-bodied participants. When looking at the performances of the prosthetic simulator users and the real prosthesis users, there are indications that the use and control is comparable. The scores of the prosthetic simulator users on the functional test SHAP in *Chapter 4* are found to be similar to scores of real prosthesis users in *Chapter 6* and in another study performed by Kyberd et al.[72] Moreover, the kinematic profiles of the prosthetic simulator users in *Chapter 4* look quite similar to the kinematic profiles found in real prosthesis users reported in *Chapter 2* and *Chapter 6* and in the studies of Fraser and Wing.[24,25] Combining the advantages of using the simulators with the similarities with real prosthesis users, it seems to be justified to use prosthetic simulators when studying learning processes and manipulating interventions by applying motor learning principles.

An evidence-based guideline

Based on the results from the studies presented in this thesis it has been possible to identify evidence-based components of training. Using these components, a training guideline was developed that can be used by therapists in the rehabilitation of prosthesis users. The guideline is intended to be the first evidence-based guideline for training of prosthesis users. It provides specific tools for the training of the control of an upper-limb prosthesis. The guideline is divided into two parts: a short part with specific training aspects and an extended background section with more information about the training aspects as discussed in this final chapter. The three stages of the rehabilitation process, the pre-prosthetic phase, the prosthetic phase, and evaluations, are followed in the guideline. The guideline can be found in the Appendix of this thesis, and contains, amongst others, the following clinical implications.

Clinical implications

- The learned control of a myoelectric hand is irrespective of the type of training; with a virtual hand, a practice hand, or a prosthetic simulator. Virtual training is recommended to cover a considerable part of the training because of several advantages over the other types of training

- Prosthetic users may differ in learning capacity. This should be taken into account when designing the training and choosing an appropriate type of control for each patient.
- During training of grasping with a prosthetic hand, the focus should be on the timing between hand opening and hand closing, and on the simultaneous ending of the reach and the grasp. These aspects will improve the timing and fluency of the movement and result in shorter movement times, and thus faster performance
- A more proficient prosthesis user tends to look less at the hand than a less skilled prosthesis user. Gaze behavior might therefore be a measure of performance to determine skill level.
- It is not always beneficial to provide much information; too much feedback might even prevent effective learning. Therefore, one should carefully deal with the provision of information. Feedback about the end result of a movement will enhance transfer of the learned skill
- Learning of grip force control is a gradual process that takes a lot of time. Ample time will be needed to achieve a good level of grip force control during rehabilitation
- Learning of grip force control should start with indirect grasping, as information from the sound hand can be used to scale the grip force applied with the prosthetic hand. Moreover, one should start with objects that allow the production of high grip forces
- Training should be structured in a blocked-repeated fashion. Starting with blocks of trials of tasks that are then concatenated and repeated will result in the best performance after training

Future directions

The use of kinematic evaluations of performance helped us to get deeper insight into the performance and skill level of the prosthesis users. Like Heckathorne[73] we advocate the use of kinematic analyses in addition to the standard clinical measures. More detailed and objective information can then be obtained which helps to better understand the overall performance of prosthesis users. Moreover, the use of kinematics can help to obtain deeper insight in the motor learning processes that take place when learning a new skill, such as learning to use a prosthesis. Measures of variability over training can then be applied, and specific methods to analyze performance over learning such as in *Chapter 5,* help to monitor performance over time.[66,74,75] The application of motor learning principles such as exploring the influence of feedback or the structure of the training, can help to maximize learning as well. Thus, when studying prosthesis use and learning to use a prosthesis, it is recommended to use clinical and kinematic levels of description as well as motor learning principles, to get maximum insight in performance and motor learning.

This thesis focused on studies to improve the functionality of prostheses through training. This is not the only aspect that needs to be maximized however. Function of prostheses, i.e., the technical aspects, need to be optimized as well. These two elements, functionality and function, are tightly coupled when trying to achieve the highest possible functional use of prostheses. To date, prostheses are not much more than tools that can assist during activities, rather than a real replacement of the lost limb. A lot of research and developments are required before prostheses become devices that will replace the human limb fully. Research would profit from improved collaborations of different rehabilitation centers to maximize sample size and enhance the validity of the studies.[76] When evidence-based guidelines such as the one that was developed as a result of the studies in this thesis, are used in several rehabilitation centers, not only will prosthesis users be brought to the highest possible level of functionality, also the rehabilitation can coincide with data collection and measurements to evaluate the efficiency of such guidelines across multiple centers. This enables research which can provide new insights in the field of prosthetics.

Based on the studies in this thesis directions for further research can be provided in order to explore additional components of training that could be added to evidence-based guidelines:

- Further research is needed towards the transfer of virtual environments to real world situations: do the skills that are learned in the virtual environment transfer to the real world situation of handling the prosthesis in everyday life?
- Training programs would benefit from the development of a test that helps to discriminate between fast and slow learners and the ability of learning. Such a test would enable the individualization of the training schedules to the motor capabilities of a prosthesis user and helps to select the best prosthetic options
- The gaze behavior could be further investigated to find out whether it is possible to speed up the learning process when one trains the use of gaze of expert prosthesis users
- Only one aspect of augmented feedback is investigated in this thesis. There are more factors associated with the delivery of the feedback which could be explored further for their role in enhancing learning, such as the

timing of the feedback (concurrent or terminal), and the frequency of the feedback (100% of the time or less than 100% of the time)

- The role of instructions is not addressed, which is interesting as well as the attentional focus could play a significant role in the learning process

Conclusion

The collective studies presented in this thesis have added to our understanding of the learning processes during skill acquisition of upper-limb prosthesis use. With the evidence-based components of training that are identified, an evidence-based training guideline was developed that can be used in the rehabilitation of myoelectric prosthesis users.

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Appendix

The results of the research presented in this thesis are combined and translated into a guideline that can be used in rehabilitation practice. The aim of the guideline is to provide a scientifically based, general structure to the training with an upper-limb prosthesis during the rehabilitation process.

The goal of the training guideline is to enhance motor learning with a prosthesis. By using the principles from the guideline in the rehabilitation process, motor learning can be maximized which will result in a permanent change in the motor abilities and the performance of the prosthesis user. The learned abilities in the clinic can then be generalized to new situations and new tasks in everyday life. Although the use of scientific research is not yet standard in clinical prosthetics practice, this can make a significant contribution to the rehabilitation of novice prosthesis users.

The guideline provides specific tools for the training of the control and functional use of an upper-limb prosthesis. For now, it focuses primarily on people with a transradial amputation or reduction deficiency who are going to use a myoelectric arm prosthesis. However, the program can, with some adjustments, also be applied to other levels of amputation or other types of prostheses, such as the recently commercialized multi-articulated hands.

When the guideline will be used in several rehabilitation centers, not only prosthesis users will be brought to the highest possible level, but also the rehabilitation can coincide with data collection and measurement to evaluate the efficiency of this guideline across multiple centers. This enables further research which can provide new insights in the field of prosthetics.

The guideline is presented on the following website, from which a pdf document can be downloaded:

www.myoprosthesistraining.info

Summary

Replacement of the hand

When a hand is missing due to amputation of the upper-limb or a congenital deficiency, many functions are affected that most take for granted. The human hand plays an essential role in our lives: we use it for all kinds of activities during the day, such as feeling, grasping, and communicating. Although we experience the use of our hands as being simple, the hand is so complex that a full replacement of the hand does not exist and will not exist for a long time to come. An upper-limb prosthesis can restore some of the functions that are lost, although the prostheses that are currently commercially available are markedly different from the human arm and hand in terms of design and control. It is a challenge for prosthesis users to learn to handle their prosthesis in a dexterous form. This is quite difficult as indicated by the high percentage of users who end up not using their prosthesis in daily life.

Training can increase the use and functionality of a prosthesis, but to date it is not known what the most efficient way of training is. The highest skill level in prosthesis use is obtained with a training that is based on scientific research. Such an evidence-based training could be developed based on knowledge on how people handle and learn to handle a prosthesis. Yet studies regarding learning to use a prosthesis are sparse. The aim of the present thesis is to increase our understanding of the learning processes during skill acquisition with a prosthesis and to identify evidence-based components of training which can subsequently be used to guide novice prosthesis users to the highest possible skill level.

Understanding how one learns to use a prosthesis

In order to increase the functionality of a prosthesis with an evidence-based training, insight into two aspects is required. First, it is necessary to understand how movements are performed with a prosthesis. Therefore, in *Chapter 2* movements made by experienced prosthesis users are described and compared with movements made with able-bodied arms and hands. The prosthetic movements were performed less smoothly, required more time, were asymmetric, and showed more decoupling of the reach and the grasp components during prehension. Moreover, timing of hand closing was delayed, leading to a characteristic plateau bridging hand opening with hand closing. To improve functional use of a prosthesis during training, attention should be paid to these specific aspects that are characteristic to prosthesis use, in particular to learning to coordinate the reach and the grasp component in prehension and the coordination of the hand opening and closing.

The second aspect that plays an important role in the development of an evidence-based training program is insight in the learning processes that underlie skill acquisition with a prosthesis. This insight is required in order to identify proper training components. In *Chapters 3 to 5* the learning processes throughout the rehabilitation process are examined with the use of a prosthetic simulator (Figure 1). This simulator was worn by able-bodied participants, enabling us to study more people than just the very few novice prosthesis users.

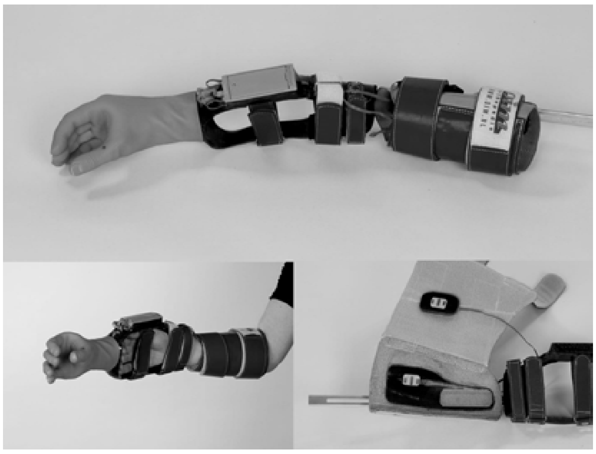


Figure 1. The myoelectric prosthetic simulator which consists of a myoelectric hand from Otto Bock, connected to an open socket in which the hand can be placed and an in-length adjustable splint which runs across the forearm. Design and construction: OIM Orthopedie Haren, The Netherlands.

Chapter 3 focuses on the training possibilities in the period before a prosthesis is fitted, which is called the preprosthetic phase of the rehabilitation. The chapter shows that for overall prosthetic performance it does not matter what type of training is utilized, whether one trains with a practice hand, a virtual hand, or with a fitted prosthesis. Because virtual training has practical and financial advantages over the other types of training, it is recommended to cover a considerable part of the training in the preprosthetic phase by virtual training. An interesting finding was that after training some participants were more proficient in the control of the hand than others. These differences in learning capacity should be taken into account when designing an individualized training program.

In *Chapter 4* the learning processes in rehabilitation are explored further in the prosthetic phase which commences after fitting of the prosthesis. To find out how learning takes place for individual training tasks, participants practiced either direct grasping with the prosthetic simulator, indirect grasping by handing over objects from the nondisabled hand to the prosthetic hand, fixating, or a combination of all three tasks during five training sessions that were spread out over two weeks. Changes in performance over time are described using end point kinematics, joint angles, grip force control and a functional test—the Southampton Hand Assessment Procedure (SHAP)—which provides an insight into how characteristics of the prosthesis are incorporated in the movements. Performance in SHAP improved after training. Improvement in global positioning with the prosthesis leveled off after three days of practice, whereas learning grip force control required more time. Moreover, the participants who practiced indirect grasping performed better than the others. Therefore, when training grip force it is best to start training handing over objects from the nondisabled hand to the prosthetic hand. Using this method the wearer can use information from the sound hand about the object to be grasped. Furthermore, one should be aware that learning fine control aspects such as grip force takes a lot of time during rehabilitation.

Chapter 5 continues examining the grip force control, which is the most difficult aspect of learning to use a prosthesis because the wearer does not receive feedback from a prosthesis. Grip force control was trained with a virtual game during five sessions in a two-week period, in which participants received either feedback about the outcome of their performance or about their movement execution. Several test-tasks that assessed different aspects of grip force control were administered before and after training. Results show that the performance increased during training while the variability in performance decreased. Grip force control only improved in the test-tasks that were similar to the training in terms of information provided, which shows that the learned skills were task-specific. Furthermore, the study shows that starting the training with a task that required low force production decreased transfer of the learned grip force. The type of information received influences the performance after training: the grip force control decreased when feedback was provided about the movement execution, whereas feedback about the outcome of the performance improved the grip force control after training. Thus, it might be better to provide information on just the outcome of performance during rehabilitation.

Further directions to enhance the learning process

Next to uncovering of the learning processes it is also useful to know what determines skill level of a prosthesis user. This knowledge can provide directions to the learning process during rehabilitation. Therefore the level of performance of experienced prosthesis users is measured in *Chapter 6* using a combination of several outcome measures including a clinical test (SHAP) and kinematic measures, which provides a wide range of information. Results show that the SHAP is a good measure of skill level of prosthesis users, whereas the more fundamental kinematic measures provide deeper insight into the performance and skill level. A higher score on SHAP was accompanied by movements that deviated less from nondisabled movements, with shorter movement times, higher peak velocities of the reach, and shorter plateau times between hand opening and hand closing. Also, the participants that reached higher SHAP scores showed better grip force control and looked less at their hand during task execution. Time was found to be a parameter that can be used to identify skilled prosthesis use, especially the duration of the plateau between hand opening and hand closing. The identification of parameters is useful during rehabilitation because they allow therapists to identify training targets for the parameters on which a user performs poor, for example to reduce the duration of the plateau by focusing on the coordination of opening and closing of the hand.

Chapter 7 changes focus to studying how practice tasks should be presented to learners. Training was examined with two groups that practiced tasks either in a blocked order, in which one task was often practiced before the next task was introduced, or a random sequence in which all tasks were practiced together. Blocked practice led to more rapid improvements early in training, although the structure in which participants practiced did not influence the performance after training. Because of the more rapid early improvements, it is recommended to start practicing in a blocked fashion at the start of the rehabilitation to keep the patient motivated.

Evidence-based training

In *Chapter 8* the results from the studies presented in this thesis are discussed, resulting in the identification of evidence-based components of training. Using these components, a training guideline was developed. The guideline contains, amongst others, the following clinical implications:

- Attention should be paid to the simultaneous ending of the reach and the grasp, and the timing between hand opening and hand closing in order to improve timing and fluency of the movements and faster performance.
- For overall prosthetic performance it does not matter what type of training is utilized in the preprosthetic phase. It is recommended to cover a considerable part of the training by virtual training though, because of practical and financial advantages over the other types of training.
- Prosthetic users may differ in learning capacity. This should be taken into account when designing the training and choosing an appropriate type of control for each patient.

- Learning of grip force control should start with indirect grasping, because the wearer can then use information from the sound hand to scale the grip force applied by the prosthetic hand.
- Learning of grip force control is a gradual process that takes a lot of time. Ample time will be needed to achieve a good level of grip force control.
- It is not always beneficial to provide much information; too much feedback might even prevent effective learning. It might therefore be better to provide information on just the outcome of performance during rehabilitation.
- A more proficient prosthesis user tends to look less at the hand than a less skilled prosthesis user. Gaze behavior may be used as one of the measures of performance that can be used to determine skill level.
- Training should be structured in a blocked-repeated fashion. Starting with blocks of task trials that are concatenated and repeated will result in the best performance after training.

More details regarding the training guideline can be found in the Appendix of this thesis. Therapists can use the guideline in the rehabilitation of prosthesis users in order to achieve the highest effects of learning such that prosthesis users will be able to apply the skills that are learned in the clinic to their everyday situation.

Samenvatting

Vervanging van de hand

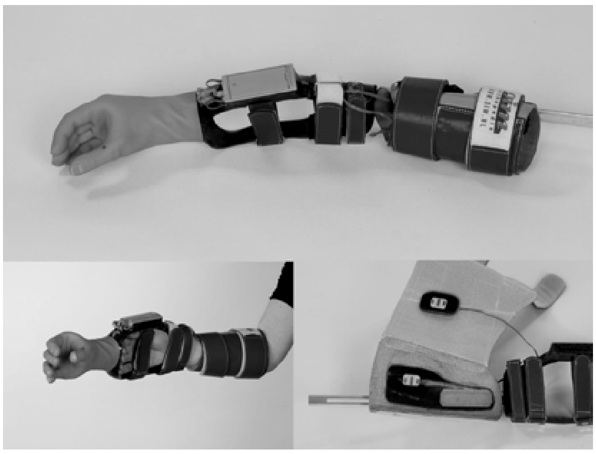
Onze handen zijn prachtige onderdelen van ons lichaam en spelen een essentiële rol in ons leven. Denk maar eens aan alle activiteiten die de hele dag met het grootste gemak uitgevoerd worden met de hand, zoals grijpen, vasthouden, voelen en aanraken, maar denk ook aan de belangrijke rol van handen bij het communiceren. Helaas zijn er mensen die maar één hand hebben of zelfs geen handen door een amputatie of een aangeboren afwijking. Voor deze mensen zijn veel van de activiteiten die we als zo vanzelfsprekend beschouwen slecht of helemaal niet uit te voeren. Een armprothese kan gebruikt worden om een deel van de verloren gegane activiteiten en functies te herstellen. Maar de menselijke hand is zo complex dat een volledige vervanging van de hand niet bestaat en het zal nog lang duren voor die gemaakt kan worden, als het al mogelijk is. De prothesen die op dit moment op de markt zijn verschillen daardoor behoorlijk van de menselijke arm en hand op het gebied van design en controle. Dit maakt dat het een grote uitdaging is voor prothesegebruikers om een prothese op een vaardige manier te leren gebruiken. Dat dit vrij moeilijk is, blijkt wel uit het hoge percentage prothesegebruikers (20% tot 40%) die uiteindelijk hun prothese niet of nauwelijks gebruiken in het dagelijks leven.

Door training kan het gebruik en de functionaliteit van een prothese verhoogd worden, maar tot op heden is het niet bekend wat de meest efficiënte manier van trainen is. Het beste vaardigheidsniveau met een prothese kan worden verkregen met een training die gebaseerd is op resultaten uit wetenschappelijk onderzoek, ook wel 'evidence-based' genoemd. Een evidence-based training kan worden ontwikkeld met kennis over hoe mensen nu eigenlijk omgaan met een prothese. Helaas zijn er maar weinig studies geweest die hebben gekeken naar hoe men een prothese leert gebruiken. Het doel van dit proefschrift is om deze leemte op te vullen en meer inzicht te krijgen in de leerprocessen tijdens het verwerven van vaardigheden met een prothese, om vervolgens evidence-based componenten van training te identificeren die gebruikt kunnen gaan worden om nieuwe prothesegebruikers naar het hoogst haalbare vaardigheidsniveau te begeleiden.

Begrijpen hoe men een prothese leert gebruiken

Om de functionaliteit van een prothese te verhogen met een evidence-based training is het nodig om inzicht te krijgen in twee aspecten. Ten eerste is het belangrijk om te begrijpen hoe bewegingen worden uitgevoerd met een prothese. Daarom zijn in *Hoofdstuk 2* de bewegingen van ervaren prothesegebruikers beschreven en vergeleken met bewegingen gemaakt door 'normale' proefpersonen met niet-aangedane armen en handen. Met de prothese werden reik- en grijptaken minder vloeiend uitgevoerd, kostten de bewegingen meer tijd, en waren de bewegingen slechter gecoördineerd. Dit was te zien aan de asymmetrie in de beweging en de ontkoppeling van de reik- en grijpcomponent die daardoor niet meer gelijktijdig verliepen. Bovendien was het sluiten van de hand vertraagd waardoor er een plateau ontstond tussen de handopening en handsluiting waarbij de hand een tijd in dezelfde stand open bleef staan. Deze verschillen met het 'normale' reiken en grijpen zijn karakteristiek voor prothesegebruik. Tijdens de training zal aandacht gegeven moeten worden aan deze specifieke aspecten om het functionele gebruik van een prothese te kunnen verhogen. Vooral het leren coördineren van de reik- en de grijpcomponent waardoor ze gelijk eindigen en het opeen laten volgen van de handopening en de handsluiting zal de bewegingen met de prothese verbeteren.

Het tweede aspect dat een belangrijke rol speelt in de ontwikkeling van een evidence-based trainingsprogramma is het begrijpen van de leerprocessen die ten grondslag liggen aan het leren gebruiken van een prothese. Door inzicht te krijgen in deze processen kunnen de juiste trainingscomponenten geïdentificeerd worden waarmee een training kan worden opgebouwd. In *Hoofdstuk 3* tot en met *5* zijn daarom de leerprocessen tijdens het revalidatieproces bekeken met behulp van een prothesesimulator (Figuur 1). Deze simulator is speciaal ontwikkeld om gebruikt te kunnen worden door niet-geamputeerde, gezonde proefpersonen waardoor we een veel grotere groep mensen konden bestuderen dan het kleine aantal prothesegebruikers.



Figuur 1. De myo-electrische prothesesimulator, bestaande uit een myo-electrische hand van Otto Bock, verbonden aan een open koker waarin de hand geplaatst kan worden en een in de lengte verstelbare spalk die aan de onderarm bevestigd wordt. Ontwerp en constructie: OIM Orthopedie Haren, Nederland.

Hoofdstuk 3 richt zich op de trainingsmogelijkheden in de periode voordat de prothese aangemeten wordt, de préprothesefase van de revalidatie. In dit hoofdstuk is aangetoond dat voor de algemene controle van de prothese het niet uitmaakt welk type training gegeven wordt, of men nu traint met een oefenhand, een virtuele hand of een aangemeten prothese. Er wordt wel aangeraden om een aanzienlijk deel van de préprothesetraining uit te voeren met een virtuele training vanwege de praktische en financiële voordelen ten opzichte van de andere trainingstypes. Een interessante bevinding in *Hoofdstuk 3* was daarnaast dat sommige mensen na het trainen de prothesehand beter konden controleren dan anderen. Het feit dat mensen kunnen verschillen in leervermogen zou meegenomen moeten worden bij het opzetten van individuele trainingsprogramma's.

In *Hoofdstuk 4* zijn de leerprocessen in de prothesefase van het revalidatieproces onderzocht. Proefpersonen oefenden het direct grijpen van objecten met de prothesehand, indirect grijpen door het overgeven van objecten van de niet-aangedane hand naar de prothesehand, fixeren van objecten, of een combinatie van alle drie de typen trainingstaken. Ze trainden met een prothesesimulator tijdens vijf sessies die verspreid waren over twee weken. Met behulp van bewegingsregistratie werden de bewegingen van de prothesehand, de hoeken van de elleboog en de schouder, en de controle van de grijpkracht bekeken om veranderingen in de uitvoering van de bewegingen over de tijd te beschrijven. Daarnaast werd voor en na de trainingen een functionele test—de Southampton Hand Assessment Procedure (SHAP)—afgenomen om de verbeteringen in het functioneren met de prothese vast te leggen. Na de trainingen werd beter gescoord op de SHAP test. Tijdens de trainingen was te zien dat het globale positioneren van de prothese in de ruimte verbeterde gedurende de eerste drie trainingen maar dat daarna weinig verbetering meer werd behaald, terwijl het leren van de grijpkracht meer tijd kostte. Men moet er daarom bewust van zijn dat het leren van fijne controle met de prothese zoals grijpkracht behoorlijk wat tijd vergt tijdens de revalidatie. De grijpkracht werd beter gecontroleerd door de proefpersonen die indirect grijpen oefenden. Het is daarom aan te raden om te starten met het overgeven van objecten van de niet-aangedane hand naar de prothesehand wanneer de grijpkracht getraind wordt. Op deze manier kan de prothesegebruiker informatie krijgen over het object via de eigen, niet-aangedane hand.

De grijpkracht is één van de moeilijkste aspecten om te leren controleren omdat de prothesegebruiker geen feedback van de prothese ontvangt. Tegelijkertijd is een goede grijpkracht erg belangrijk voor het goed functioneren met de prothese.

Daarom gaat *Hoofdstuk 5* verder in op het leren controleren van de grijpkracht. Proefpersonen trainden de controle van de grijpkracht met een virtueel spel tijdens vijf sessies in twee weken tijd, waarbij ze feedback kregen op het eindresultaat, oftewel de uitkomst van de uitvoering, of op de uitvoering van de taak zelf. Voor en na de trainingen werden verscheidene test-taken afgenomen om verschillende aspecten van de grijpkrachtscontrole te testen. Analyse van de resultaten laat zien dat de proefpersonen beter werden tijdens het trainen terwijl de variabiliteit in de uitvoering afnam. Starten met een taak waarbij kleine grijpkrachten geproduceerd moeten worden, wat moeilijk is bij een prothese, zorgde voor een slechtere prestatie na afloop van de trainingen ten opzichte van starten met grotere krachten. Daarnaast was er alleen verbetering te zien in de test-taken die gelijke type informatie gaven als de trainingen, wat laat zien dat er taak-specifiek geleerd is. Het type informatie had ook invloed op de prestaties na de training: de mate van controle van de grijpkracht verminderde wanneer feedback werd gegeven over de uitvoering van de beweging, terwijl feedback over de uitkomst van de uitvoering de grijpkrachtscontrole verbeterde. Dit geeft aan dat het beter zal zijn om niet teveel feedback te geven tijdens de revalidatie, maar alleen informatie over het resultaat van de uitvoering of de prestaties.

Verdere aanbevelingen om het leerproces te verbeteren

Naast het blootleggen van de leerprocessen is het ook nuttig om te weten welke parameters bepalend zijn voor het vaardigheidsniveau van een prothesegebruiker. Deze kennis kan gebruikt worden tijdens de revalidatie om de focus van het trainingsproces bij te sturen. Daarom is het prestatieniveau van ervaren prothesegebruikers gemeten in *Hoofdstuk 6*. Door een combinatie van verscheidene uitkomstmaten te gebruiken zoals een klinische test (SHAP) en metingen van de bewegingen (kinematica) van de prothese werd een breed scala aan informatie verzameld. De resultaten lieten zien dat SHAP een goede test is om het vaardigheidsniveau van prothesegebruikers te meten, terwijl de meer fundamentelere kinematische maten dieper inzicht gaven in waarom iemand een bepaalde score kreeg op de klinische test. Prothesegebruikers die hoger scoorden op SHAP hadden bewegingen die minder afweken van bewegingen met normale, niet-aangedane armen en handen. De bewegingstijden waren korter, de reikbewegingen waren sneller en er waren kortere plateautijden tussen handopening en handsluiting waardoor de totale beweging er vloeiender uitzag. Ook hadden de prothesegebruikers met een hogere score op SHAP betere controle over de grijpkracht en ze keken minder naar hun hand. De factor tijd werd geïdentificeerd als parameter wat gebruikt kan worden om de vaardigheid van prothesegebruik te bepalen. Vooral de duur van het plateau tussen hand opening en handsluiting bleek bepalend te zijn voor de mate van vaardigheid met de prothese. Het identificeren van parameters is handig tijdens het revalidatieproces omdat therapeuten op die manier eenvoudig trainingsdoelen kunnen vaststellen voor de parameters waar iemand slecht op scoort. Om bijvoorbeeld de duur van het plateau te verminderen kan de therapeut tijdens het trainen de focus leggen op de coördinatie van het grijpen door de handsluiting direct te laten volgen op de handopening.

Hoofdstuk 7 verlegt vervolgens de focus naar de structuur van de training door te bestuderen hoe taken het beste kunnen worden gepresenteerd. Twee trainingsstructuren werden met elkaar vergeleken. Een groep proefpersonen oefende taken in een geblokte volgorde—waarin een taak vaak werd geoefend voor de volgende taak werd geïntroduceerd—terwijl de andere groep oefende in een variabele structuur waarbij alle taken in willekeurige volgorde door elkaar werden geoefend. Geblokt oefenen leidde tot snellere verbeteringen vroeg in de training. Maar na afloop van de training verschilden de twee groepen niet meer van elkaar en bleek de structuur waarin getraind werd de prestaties niet te beïnvloeden. Door de snelle verbetering in het begin wordt er aangeraden om te starten met een geblokte volgorde om de prothesegebruiker te motiveren, gevolgd door een geblokt-herhaalde structuur.

Evidence-based training

In *Hoofdstuk 8* zijn de resultaten van de onderzoeken in dit proefschrift samengevat, wat heeft geleid tot de identificatie van evidence-based componenten voor training. Met behulp van deze componenten is een trainingsrichtlijn ontwikkeld. De richtlijn bevat onder andere de volgende klinische implicaties:

- Geef aandacht aan de coördinatie van het reiken en grijpen en de handopening en handsluiting, door te trainen op het gelijktijdig eindigen van het reiken en grijpen en het snel opeen laten volgen van de handsluiting op de handopening. Dit zal de timing en de vloeiendheid van de bewegingen verbeteren en de totale beweging versnellen.
- Voor algemene controle van de prothesehand maakt het niet uit wat voor type training wordt gebruikt in de préprothesefase. Wel wordt aangeraden om een groot deel van de training virtueel uit te voeren omdat virtueel trainen praktische en financiële voordelen heeft ten opzichte van de andere typen trainingen.
- Prothesegebruikers kunnen verschillen in leervermogen. Hier zou rekening mee moeten worden gehouden bij het opzetten van de training en bij het kiezen van een geschikt prothesetype voor elke nieuwe prothesegebruiker.

- Het leren van de grijpkracht zou moeten beginnen met indirect grijpen omdat de prothesegebruiker dan informatie vanuit de niet-aangedane hand kan gebruiken om de grijpkracht van de prothesehand te leren schalen.
- Het leren controleren van de grijpkracht is een geleidelijk proces dat veel tijd in beslag neemt. Er zal veel tijd geïnvesteerd moeten worden tijdens de revalidatie om een goede controle van de grijpkracht te bereiken.
- Het is niet altijd voordelig om veel informatie te geven tijdens training; te veel feedback kan zelfs het leren verhinderen. Het is daarom beter om alleen informatie over het resultaat van de uitvoering te geven tijdens de revalidatie.
- Een vaardiger prothesegebruiker kijkt minder vaak naar de prothesehand dan een minder vaardige gebruiker. Het kijkgedrag zou daarom gebruikt kunnen worden als een van de maten om het vaardigheidsniveau van een prothesegebruiker te bepalen.
- Training zou moeten worden gestructureerd op een geblokt-herhaalde wijze. Het starten met blokken van taken die vervolgens aaneengeschakeld en herhaald worden, zal waarschijnlijk de beste prestaties na training opleveren.

Meer informatie over de ontwikkelde trainingsrichtlijn is te vinden in de Appendix van dit proefschrift. De richtlijn kan worden gebruikt door therapeuten in de revalidatie van prothesegebruikers om de beste leereffecten te behalen zodat prothesegebruikers de vaardigheden die ze geleerd hebben in de kliniek toe kunnen passen in hun dagelijks leven.

Dankwoord

Dit proefschrift is tot stand gekomen met hulp van heel veel mensen. Mijn dank is dan ook groot voor iedereen die op wat voor manier dan ook heeft bijgedragen maar wie ik niet persoonlijk noem.

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Curriculum Vitae

Hanneke Bouwsema werd geboren op 22 november 1982 te Marum. Na het behalen van haar VWO diploma aan de Borgen in Leek is ze in 2001 begonnen aan de studie Bewegingswetenschappen aan de Rijksuniversiteit van Groningen. In 2005 heeft ze haar diploma gehaald met als afstudeerproject 'Understanding the control processes underlying prehension with an upper extremity prosthesis'. Vervolgens is ze de verkorte opleiding Fysiotherapie aan de Hanzehogeschool in Groningen gaan volgen. Nog tijdens deze opleiding is ze in 2007 een pilotstudie gaan uitvoeren bij Bewegingswetenschappen als vervolg op haar afstudeerproject. Naar aanleiding van deze pilotstudie is een promotieonderzoek opgestart, gefinancierd door de firma Otto Bock (Wenen, Oostenrijk). Van november 2008 tot en met september 2013 is Hanneke als promovendus aan het werk geweest bij het Centrum voor Bewegingswetenschappen en de afdeling Revalidatiegeneeskunde van het UMCG. Vanaf januari 2014 is Hanneke aan het werk als senior onderzoeker bij het Kenniscentrum van Adelante Zorggroep in Hoensbroek.

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